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Pre-Restoration Geomorphic Characteristics of Minebank Run, Baltimore County, Maryland, 2002–04

Scientific Investigations Report 2007–5127

U.S. Department of the Interior
U.S. Geological Survey

Cover. Top photograph taken in June 2004 at station 0158397967, Minebank Run near Glen Arm, Maryland. View is looking upstream at the stream channel from the station location. Bottom photograph taken in October 2004 at the same location and same view after the stream restoration was completed in this area. (Photographs by Edward J. Doheny, U.S. Geological Survey.)

Pre-Restoration Geomorphic Characteristics of Minebank Run, Baltimore County, Maryland, 2002–04

By Edward J. Doheny[1], Roger J. Starsoneck[2], Paul M. Mayer[3], and Elise A. Striz[4]

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Conversion Factors, Vertical Datum, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
acre	0.004047	square kilometer
square mile (mi^2)	259	hectare
square mile (mi^2)	2.59	square kilometer
	Volume	
cubic foot (ft^3)	0.000023	acre-feet
	Flow Rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	907.2	kilogram (kg)

Temperatures in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the following equation:

$$°F = 1.8\,(°C) + 32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Water year is defined as the 12-month period beginning October 1 and ending September 30. The water year is designated by the calendar year in which it ends. For example, the year beginning October 1, 2003 and ending September 30, 2004 is called “water year 2004.”

List of Abbreviations

D.C.	District of Columbia
DEPRM	Department of Environmental Protection and Resource Management
d50	Median particle diameter
IES	Institute of Ecosystem Studies
I-695	Interstate 695, Baltimore Beltway
NGVD	National Geodetic Vertical Datum of 1929
R^2	Coefficient of determination
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Pre-Restoration Geomorphic Characteristics of Minebank Run, Baltimore County, Maryland, 2002–04

By Edward J. Doheny, Roger J. Starsoneck, Paul M. Mayer, and Elise A. Striz

Abstract

Data collected from 2002 through 2004 were used to assess geomorphic characteristics and geomorphic changes over time in a selected reach of Minebank Run, a small urban watershed near Towson, Maryland, prior to its physical restoration in 2004 and 2005. Longitudinal profiles of the channel bed, water surface, and bank features were developed from field surveys. Changes in cross-section geometry between field surveys were documented. Grain-size distributions for the channel bed and banks were developed from pebble counts and laboratory analyses. Net changes in the elevation of the channel bed over time were documented at selected locations.

Rosgen Stream Classification was used to classify the stream channel according to morphological measurements of slope, entrenchment ratio, width-to-depth ratio, sinuosity, and median-particle diameter of the channel materials. An analysis of boundary shear stress in the vicinity of the streamflow-gaging station was conducted by use of hydraulic variables computed from cross-section surveys and slope measurements derived from crest-stage gages in the study reach.

Analysis of the longitudinal profiles indicated noticeable changes in the percentage and distribution of riffles, pools, and runs through the study reach between 2002 and 2004. Despite major changes to the channel profile as a result of storm runoff events, the overall slope of the channel bed, water surface, and bank features remained constant at about 1 percent.

The cross-sectional surveys showed net increases in cross-sectional area, mean depth, and channel width at several locations between 2002 and 2004, which indicate channel degradation and widening. Two locations were identified where significant amounts of sediment were being stored in the study reach. Data from scour chains identified several locations where maximum scour ranged from 1.0–1.4 feet during storm events. Bank retreat varied widely throughout the study reach and ranged from 0.2 feet to as much as 7.9 feet. Sequential measurements of bed elevation in selected locations indicated as much as 2 feet of channel degradation in one location during a storm event in May 2004 and identified pulses of sediment that were gradually transported through the study reach during the monitoring period.

Particle-size analyses of channel bed materials indicated a median particle diameter of 20.5 millimeters (coarse gravel) for the study reach, with more than 24 percent being sand particles (greater than 0.062 millimeters). Analyses of bank samples showed finer-grained material composing the channel banks, predominantly silt/clay or a mixture of silt/clay (less than 0.062 millimeters) and very fine to coarse sand.

The Minebank Run stream channel was classified as a B4c channel, based on morphological descriptions from the Rosgen Stream Classification System. The B4c classification describes a single-thread stream channel with a moderate entrenchment ratio of 1.4 to 2.2; a width-to-depth ratio greater than 12; moderate sinuosity of 1.2 or greater; a water-surface slope of less than 2 percent; and a median-particle diameter in the gravel range of 2 to 64 millimeters.

Analysis of boundary shear stress indicated larger mean velocities and boundary shear stress values for Minebank Run when compared to relations for non-urban B channel types developed by Rosgen. The slope of the regression line for mean velocity versus boundary shear stress at Minebank Run was considerably less than slopes developed by Rosgen for non-urban channel types. This indicates that relatively small increases in mean velocity can result in large increases in boundary shear stress in stream channels with highly developed watersheds, such as Minebank Run.

Introduction

Minebank Run, a small urban stream in Baltimore County, Maryland, is a tributary of the Gunpowder River in the Chesapeake Bay watershed that drains approximately 3.27 mi^2 (square miles). Since the late 1990s, Minebank Run has been the focus of physical restoration efforts by the Baltimore County Department of Environmental Protection and Resource Management (DEPRM). One of the primary goals of physical restoration is to re-establish geomorphic **stability**[1] of the stream channel.

Urban streams, such as Minebank Run, commonly display **flashy** streamflow due to rapid runoff from impervious surfaces. The flashy streamflow can alter the bed and banks of

[1]Words in **bold** are defined in the glossary section of the report.

the stream channel considerably over time. The erosive power that is generated in urban streams often leads to degradation and widening of stream channels, bank failure, increased sediment supply, and instability of riffle and pool features along the channel profile (Paul and Meyer, 2001).

In April 2001, the U.S. Environmental Protection Agency (USEPA) began investigating opportunities in the Baltimore metropolitan area to study streams that were targeted for restoration to improve physical function and habitat. Baltimore was a focus area for stream restoration research because of a large number of projects that had been carried out since the early 1990s. Minebank Run was selected for study because of the opportunity to collect and interpret several different types of data before and after the channel restoration. The restoration of Minebank Run has provided an opportunity to study potential water-quality benefits from implementation of specific restoration practices, such as re-planting vegetation in riparian zones, reconfiguring of meanders and point bars, reconstruction of flood plains, and physical movement of sections of the channel within the valley. In October 2001, the U.S. Geological Survey (USGS), the USEPA, and the Institute of Ecosystem Studies (IES) jointly initiated a study to investigate the effects of stream restoration on stream hydrology, denitrification, and overall water quality in a selected reach of Minebank Run (Doheny and others, 2006). In response to rapid changes in channel geometry, elevations of channel features, and the rate of lateral migration of the stream channel observed during the first year of the study, the USGS was additionally tasked with measuring and documenting the geomorphic changes within the Minebank Run study reach prior to physical restoration.

This report describes conventional techniques that were used for collection of geomorphic data in a study reach in the Minebank Run watershed during **water years** 2002 through 2004. Continuous-record streamflow data were collected in the study reach. Geomorphic data collected in the reach included surveyed elevations of the channel bed, water surface, and bank features; surveyed cross sections; measurements of bank erosion and maximum scour by use of bank pins and scour chains; pebble counts and samples of material from the channel bed and banks for grain-size analyses; measurements of bed elevations over time in selected locations; and high-water marks from storm runoff events in the watershed.

Data collected during this study were used to assess pre-restoration geomorphic characteristics and pre-restoration geomorphic changes over time in the Minebank Run study reach. Analyses conducted for this report included (1) a comparison of changes in longitudinal profiles of the channel bed, water surface, and bank features over time; (2) a comparison of changes in cross-section geometry due to aggradation, degradation, and **lateral erosion**; (3) grain-size distribution of the channel bed and banks; (4) net changes in the elevation of the channel bed at selected locations over time; (5) classification of selected sections of the reach according to the Rosgen system of stream classification (Rosgen, 1994, 1996); and (6) **boundary shear stress** based on cross-section geometry and water-surface slope in the vicinity of the streamflow-gaging station.

Description of Minebank Run Watershed

Minebank Run is a 3.27 mi^2 sub-watershed of the Gunpowder Falls located in the south-central section of Baltimore County, Maryland, approximately 4.7 mi (miles) northwest of the **Fall Line** in the Piedmont Physiographic Province (fig. 1). The watershed lies between 39° 23' 34" and 39° 25' 26" north latitude, and between 76° 32' 07" and 76° 35' 40" west longitude. The headwaters are located on the east side of Towson, Maryland. The stream flows roughly in a northeasterly direction and confluences with Gunpowder Falls near the town of Loch Raven, approximately 0.30 mi downstream of the lower dam on Loch Raven Reservoir (Doheny and others, 2006).

The Minebank Run watershed is bounded by 2 ridges that are oriented approximately from southwest to northeast, with a broad, lightly sloping valley in between. The valley width ranges from approximately 0.6 mi near the headwater and outlet areas, to about 1.5 mi near the mid-point of the watershed. The watershed ranges in elevation from about 400 to 500 ft (feet) above sea level at the drainage boundaries, to about 150 to 400 ft above sea level in the stream valley. **Relief** ranges from 100 to 300 ft in most areas of the watershed (Doheny and others, 2006).

As of 2004, the Minebank Run watershed consisted of a restored section and an unrestored section. The upper 0.80 mi^2 of the watershed, which is upstream of the Baltimore Beltway (I-695) (fig. 1), was restored in 1998 and 1999. Restoration was initiated in the lower 2.47 mi^2 of the watershed during 2004 and was completed in 2005 (Doheny and others, 2006).

In the section of the watershed that was restored during 1998 and 1999, the dimension, pattern, and profile of the stream channel were reconstructed for purposes of improving stability. Riffle and pool sequences were re-created by selective placement of rock weirs (Rosgen, 1993), which were also intended to control sediment supply in the watershed. Where possible, flood plains were created to allow flood flows to spread out in the valley and reduce the energy directed at the channel bed. Channel-bank slopes were reduced in many locations and natural vegetation was planted on the banks. Low to moderate channel sinuosity was maintained throughout the restored reaches to reduce the potential for lateral bank erosion and failure (fig. 2). Similar techniques were used in the unrestored section of the watershed during 2004 and 2005 to reconstruct what had been a degraded and over-widened stream channel (Doheny and others, 2006).

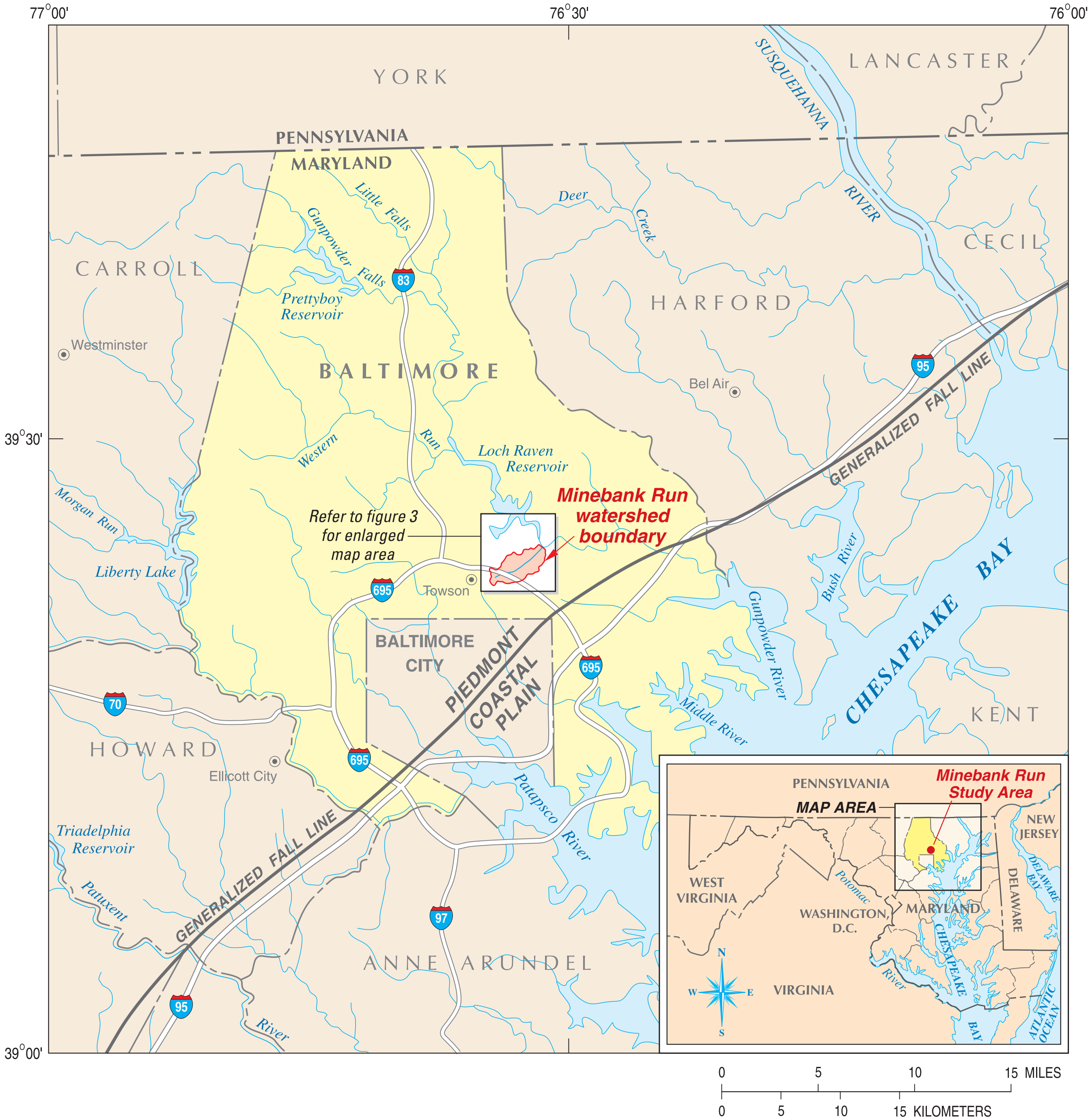

Figure 1. Location of Minebank Run watershed and study area, Baltimore County, Maryland.

Figure 2. View looking upstream at restored section of Minebank Run, just upstream of the Baltimore Beltway (I-695), 2001. (Photograph by Robert J. Shedlock, U.S. Geological Survey).

Description of Study Area

The Minebank Run study reach drains 2.06 mi^2 in the unrestored section of the watershed (fig. 3). The length of the study reach is approximately 1,800 ft. At this location, land use in the watershed is approximately 80.6 percent urban and 16.9 percent forested or open space (Baltimore County Department of Environmental Protection and Resource Management, 2000). The largest percentages of urban land use and impervious surfaces are in the headwaters of the watershed, upstream of I-695. Most of these highly impervious areas are at higher elevations near the southern section of the drainage boundary. These areas, in combination with direct runoff from I-695, are the likely sources of increased storm runoff that cause the stream stage and corresponding discharge to increase and decrease very quickly during storm events (Doheny and others, 2006).

Prior to restoration in 2004 and 2005, much of the unrestored section of Minebank Run was entrenched and over-widened (Doheny and others, 2006). Most of the stream energy was being directed at the channel bed and banks, with little or no ability for the streamflow to overtop the channel banks and spread out onto the flood plain. The channel banks were steeply sloped in many locations with numerous occurrences of bank failure and lateral erosion. The channel sinuosity in the study reach was fairly low, but several locations in the reach had large meanders that coincided with very unstable channel banks and a highly mobile and unstable channel bed (fig. 4) (Doheny and others, 2006).

Bed material in the study reach consists of a mixture of sand, gravel, cobbles, and a few small boulders. In this section of the watershed, much of the flood plain and channel bed lie within deposits of **alluvium** and **colluvium** mapped by Crowley and Cleaves (1974). Few bedrock outcrops are visible in the study reach because of the deposits of alluvium and colluvium. Bank material includes some deposits of sand and gravel, with greater percentages of silt and clay than in the channel bed.

The study reach selected for geomorphic investigation overlapped a study reach where shallow ground water and water quality have been monitored since 2001 (fig. 5) (Mayer and others, 2003). The study design for ground-water and water-quality monitoring included nests of three 1-in. (inch)-diameter **piezometers** that were installed 2 to 6 ft below the surface of the channel bed, and 3.75 to 11.85 ft below the surface of the channel banks in three selected locations along Minebank Run (fig. 5) (Doheny and others, 2006). These piezometers in the channel bed also were used in the geomorphic investigation as measuring points for tracking channel-bed elevations over time.

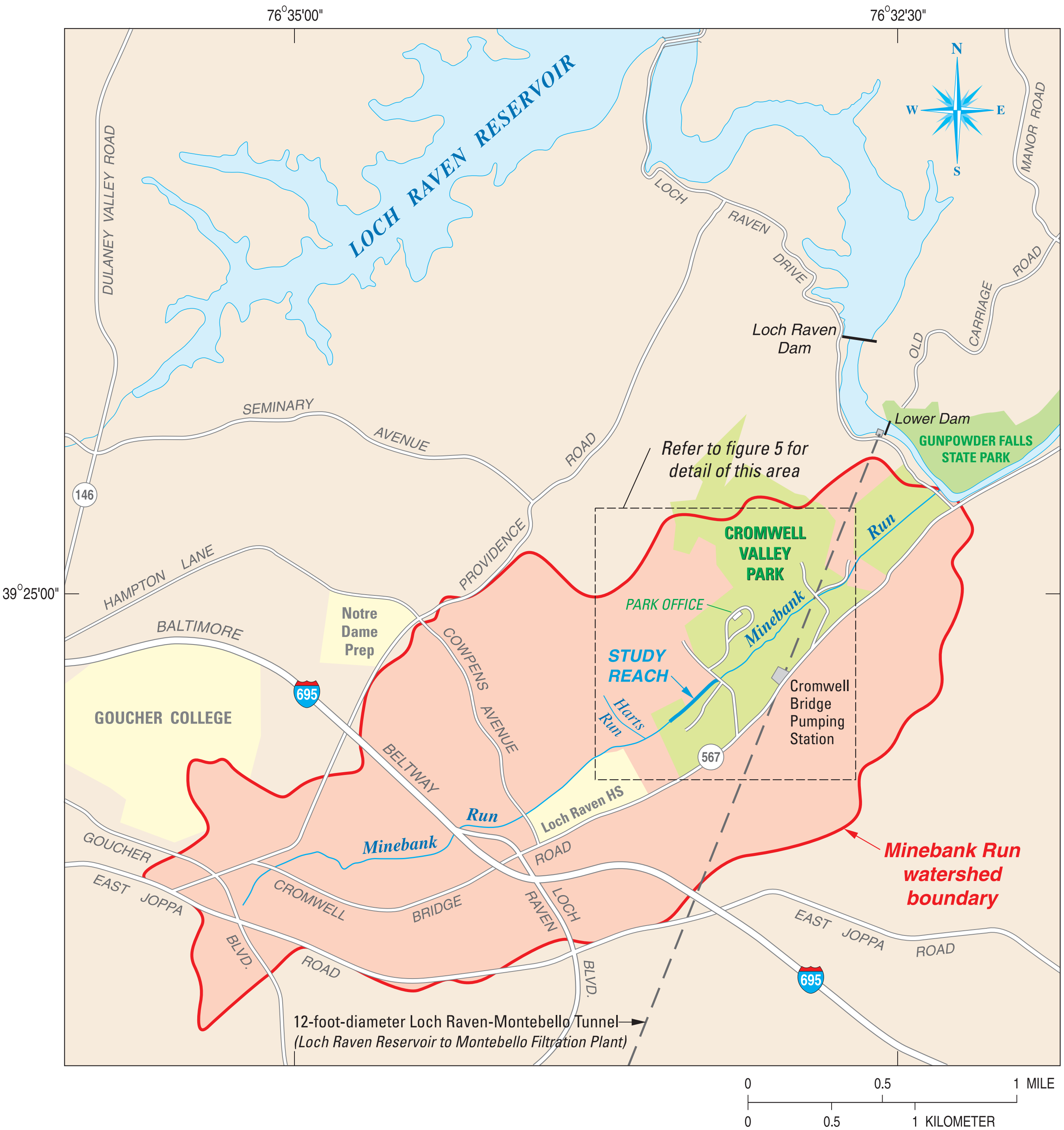

Figure 3. Detailed view of Minebank Run watershed and study reach, Baltimore County, Maryland.

Figure 4. View looking upstream at unrestored section of Minebank Run in Cromwell Valley Park, downstream of the Baltimore Beltway (I-695), 2002. (Photograph by Robert J. Shedlock, U.S. Geological Survey.)

Methods of Data Collection

Geomorphic data were collected in and near the Minebank Run study reach to quantify pre-restoration stream-channel characteristics, and to assess changes to the stream channel prior to restoration. A **continuous-record streamflow-gaging station** (USGS station number 0158397967, Minebank Run near Glen Arm, Maryland) (fig. 5) has provided 5-minute, unit-value stage and discharge data in the Minebank Run study reach since October 2001. Surveys were conducted to document existing cross-section geometry and changes in channel geometry over time. Scour chains and bank pins were installed at the cross section locations to quantify physical changes occurring between storm events. Measuring point elevations from instream piezometers were used as the elevation control in selected cross-section locations to determine the net change in channel-bed elevation over time. Surveys of the longitudinal profile were conducted to determine the elevations of channel features throughout the study reach. Pebble counts were conducted to determine grain-size distributions of the surficial bed material. Samples of the underlying channel bed material and channel banks were collected to determine grain-size distributions for selected areas. High-water marks were measured at the gaging station and at other selected locations in the study reach to determine the water-surface slope during storm events.

Streamflow

Since October 2001, continuous-record streamflow data have been collected at USGS station 0158397967 in the Minebank Run study reach using standard USGS stream-gaging techniques (Carter and Davidian, 1968; Buchanan and Somers, 1968). Periodic measurements of streamflow were made at a range of gage heights to develop a **stage-discharge rating** for the stream. The stage-discharge rating was used with the continuous record of gage heights from the station to determine the discharge of the stream continuously at 5-minute intervals. **Daily mean discharges** were determined for each day of the water year. Streamflow statistics for station 0158397967, Minebank Run near Glen Arm, Maryland for water years 2002 through 2004 are presented in table 1 (Saffer and others, 2005).

Geomorphic monitoring occurred during a relatively wet hydrologic period as the Baltimore region was recovering from severe drought conditions in the spring and summer of 2002. The long-term average for the Baltimore region is about 42 in. of precipitation (James, 1986). On the basis of precipitation data collected in the vicinity of the Minebank Run study reach, over 64 in. of total precipitation were recorded during the 2003 water year, and nearly 52 in. were recorded during the 2004 water year (Doheny and others, 2006).

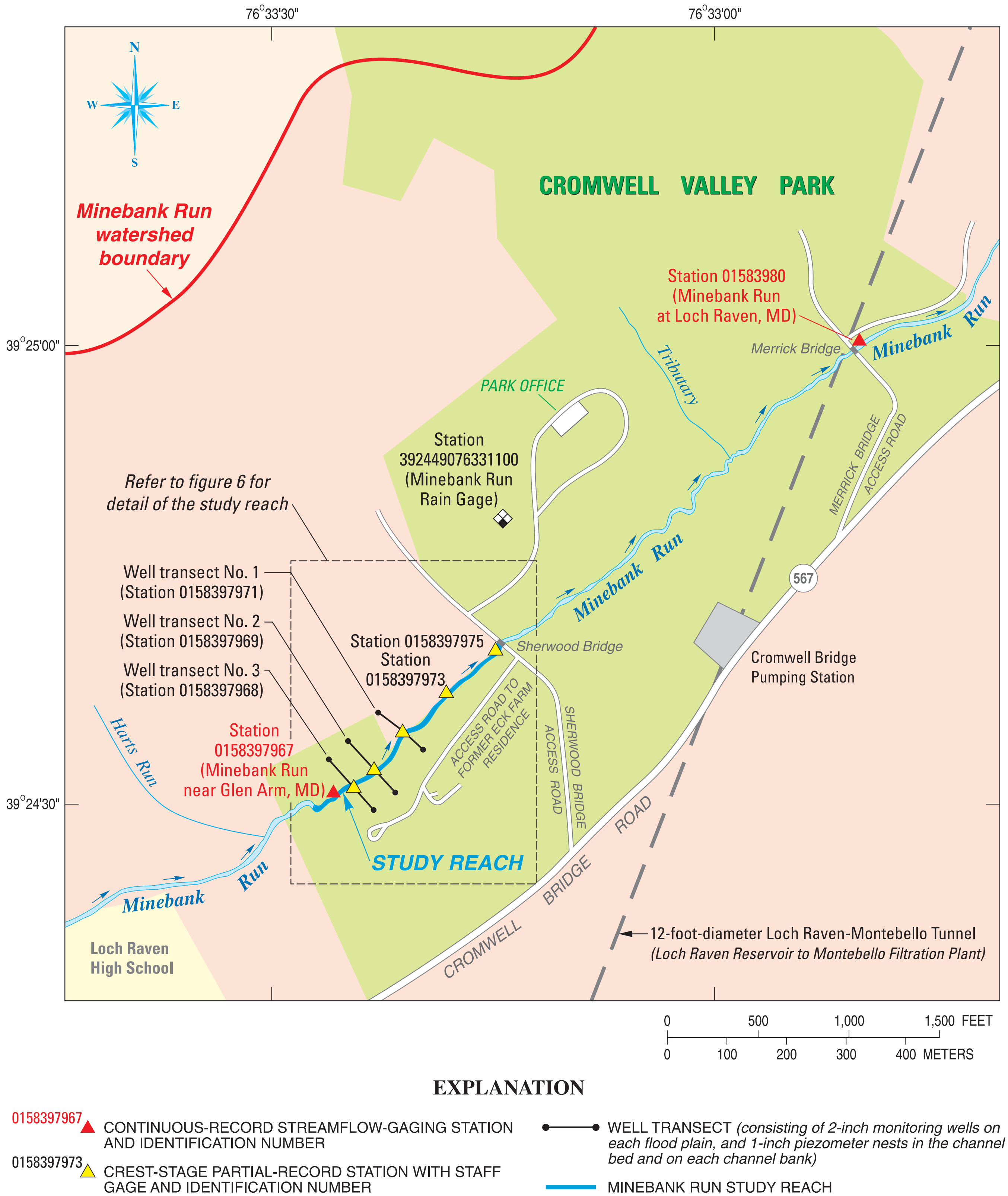

Figure 5. Location of continuous-record streamflow-gaging stations, crest-stage partial-record stations, and well transects along the Minebank Run study reach, Baltimore County, Maryland.

Table 1. Summary of streamflow statistics for station 0158397967, Minebank Run near Glen Arm, Maryland, water years 2002–04.

[mi^2, square mile; ft^3/s, cubic foot per second; [(ft^3/s)/mi^2], cubic foot per second per square mile]

	Station 0158397967, Minebank Run near Glen Arm, Md.
Drainage area (mi^2)	2.06
Annual Mean Discharge (ft^3/s)	3.25
Highest annual mean discharge (ft^3/s)	4.34 (2004)
Lowest annual mean discharge (ft^3/s)	1.15 (2002)
Highest daily mean discharge (ft^3/s)	61 (Oct. 27, 2003)
Lowest daily mean discharge (ft^3/s)	0.04 (Aug. 17, 2002)
Maximum instantaneous peak flow discharge (ft^3/s)	1,390 (Jun. 12, 2003)
Minimum instantaneous low flow discharge (ft^3/s)	0.04 (Aug. 17, 2002)
Annual runoff (inches)	21.46
Annual runoff [(ft^3/s)/mi^2]	1.58

Longitudinal Profiles

The longitudinal profile of the Minebank Run study reach was surveyed during April 2002, March 2003, and April 2004 to determine the relative elevations and consistency of channel features. The methods used are described in Leopold (1994). The reach where the longitudinal profile surveys were conducted was located between the Sherwood Bridge and just downstream of the confluence of Harts Run and Minebank Run (fig. 5). Channel-bed and water-surface elevations were surveyed along the study reach, as were channel features such as point bar surfaces, **terraces**, and top of bank elevations. All surveys were conducted using the same starting point and longitudinal stationing so that comparisons of profiles from different years would be possible. Survey elevations were measured at break points between riffles, pools, and **runs** in order to define these features individually. Distances were measured along the **thalweg** between surveyed points on the streambed, which allowed for definition of the lengths and distribution of riffles, pools, and runs in the reach. Point bar surfaces, terraces, and top of bank elevations were also surveyed in selected locations along the reach where these features were clearly identifiable. Dates, locations, and longitudinal stationing used for the longitudinal-profile surveys in the Minebank Run study reach are summarized in table 2.

Cross Sections

Permanent cross sections were established in and near the Minebank Run study reach to assess physical changes to the stream channel prior to restoration. Nine cross sections were established with monumented endpoints over a distance of approximately 1,300 ft (fig. 6) within the study reach. The reach contained the continuous-record streamflow-gaging station, and the three transects of wells and piezometers that were established for other technical aspects of the study (fig. 5). The cross sections were established in straight sections of the channel, or in straight sections between meanders, and were aligned perpendicular to the direction of streamflow. The cross sections were vertically referenced to mean sea level datum and were initially surveyed in December 2002. The cross sections were re-surveyed during June and July of 2003 in the aftermath of a major storm event that occurred in the watershed on June 12, 2003 (table 1). The cross sections were surveyed again during January and February of 2004, just prior to the start of the channel restoration work that began in June 2004. Basic station information for the nine permanent cross sections in and near the Minebank Run study reach is summarized in table 3.

Bank Erosion Pins

Changes in bank erosion and deposition over time were measured at each surveyed cross section using a series of bank erosion pins (Harrelson and others, 1994). Metal pins, approximately ½-in. thick and 2–4 ft in length, were inserted horizontally at different elevations into shear and heavily-eroded banks, with a measured length that was left exposed. At each pin, an elevation was determined by use of a rod and level. During periodic visits to each cross section, exposure of each pin was measured. If the bank had been severely eroded between site visits, the exposed pin was driven back into the bank and re-measured before leaving the site. Pin loss was documented and another pin was installed at approximately the same elevation. A sample diagram of the placement of bank erosion pins at a cross section is shown in figure 7.

Scour Chains

Scour chains were used to measure the aggradation or degradation in the thalweg of the streambed at each surveyed cross section (Harrelson and others, 1994). A known length

Table 2. Dates, locations, and longitudinal stationing used for the longitudinal-profile surveys in the Minebank Run study reach, 2002–04.

[ft, feet]

Date of survey	Starting station (ft)	Starting location	Ending station (ft)	Ending location	Reach length (ft)
April 16–17, 2002	5,000	Upstream side of Sherwood Bridge	3,358	In meander bend, approximately 330 ft upstream of gage	1,642
March 31–April 1, 2003	5,000	Upstream side of Sherwood Bridge	3,283	In meander bend, approximately 290 ft upstream of gage	1,717
April 23, 2004	5,000	Upstream side of Sherwood Bridge	3,337	In meander bend, approximately 280 ft upstream of gage	1,663

of chain was installed vertically into the unconsolidated bed material and anchored at the bottom by a horizontal pin. At the loose end, a measured length of chain was left exposed and laid over the surface of the channel bed. The number of chain links exposed on the bed was recorded as well as the measured length of exposed chain. The chains were located and excavated approximately once a month or after large storm events. The depth of fill overlying the chains was also recorded. The number of horizontal chain links and measured length of horizontal chain was recorded. If additional chain links were bent over and exposed horizontally in between site visits, this indicated scour on the channel bed. The depth of material covering the chain is indicative of subsequent deposition of channel materials that occurs on the recession of a storm event (fig. 8).

Channel Materials

The channel materials composing the bed and banks of the study reach were characterized using (1) pebble counts of the surficial channel-bed sediments at each cross section, and (2) grain-size analysis of sediment samples collected from the channel banks and the subsurface of the channel bed at each cross section.

One-hundred-particle pebble counts were conducted in the main channel at each of the nine permanent cross sections during May and June of 2003. Pebble counts were also conducted in May 2002 at the three well transects in the study reach that correspond to cross sections Ee, Ff, and Gg. The pebble counts were made by randomly picking up particles from the channel bed throughout the entire length of the main channel at an interval of about 1 particle per foot of cross section, and measuring the intermediate axis of the particle that is picked up (fig. 9) (Leopold, 1994; Harrelson and others, 1994). The particle sizes were tallied according to size class (silt, sand, gravel, or cobbles) and used to directly determine grain-size distributions for the surface of the channel bed at each cross section and for the study reach. An example of a grain-size distribution and computation of **percent finer** from a pebble count at cross section Ff in the Minebank Run study reach on June 6, 2003 is shown in table 4. A plot of the grain-size distribution developed from the pebble count is shown in figure 10.

Sediment samples were collected from the channel bed subsurface and banks at each cross section during November 2002 and shipped to the USGS sediment laboratory in Vancouver, Washington for grain-size analysis. Channel-bed samples were collected in the left, center, and right side of each cross section by (1) removing the top 2–3 in. of bed material in the location of the sample, and (2) shoveling about 6–8 in. into the bed, and filling a standard cloth sediment bag with material from the subsurface of the bed. Bank samples were collected from both channel banks. If the bank was lightly sloped, the sample was taken from the top of the bank by shoveling 6–8 in. down from the surface. If the bank was shear or severely undercut, a sample was taken from the top of the bank, and also from within the shear part of the bank (fig. 11). Samples were quantified using a standard sieve analysis for the channel-bed material and sedigraph analysis for the bank samples (Daniel J. Gooding, USGS, written commun., 2002). Sedigraph analysis was necessary to determine grain-size distributions of the bank samples due to significant percentages of fine material such as silt and clay that compose the channel banks at Minebank Run.

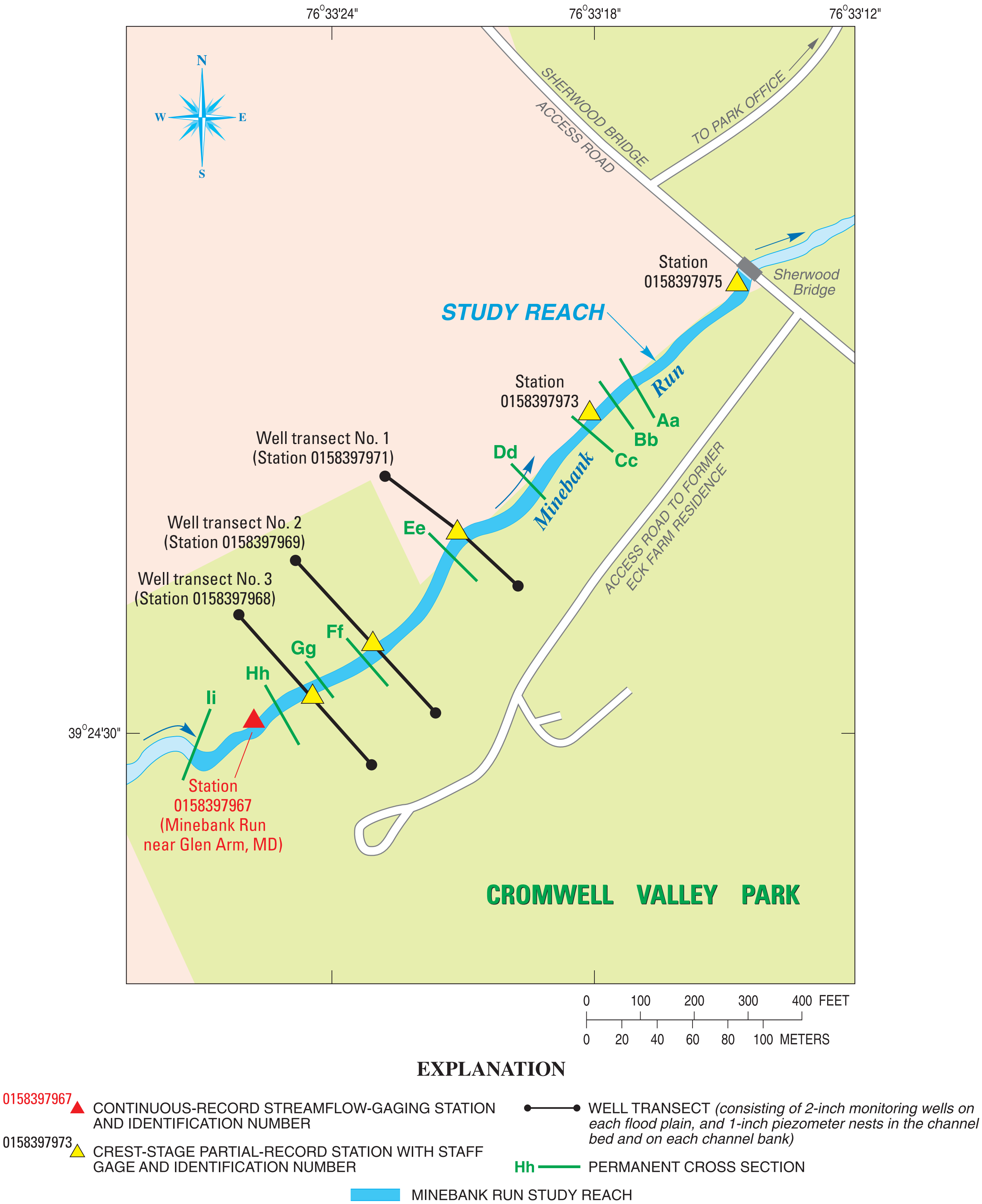

Figure 6. Locations of permanent cross sections that were established in the Minebank Run study reach at Cromwell Valley Park, 2002.

Table 3. Basic station information for permanent cross sections located in and near the Minebank Run study reach.

[Lat, Latitude; Long, Longitude; ft, feet; °, degrees; ', minutes; ", seconds]

Cross section name	Longitudinal station (ft)	Description of cross section location	Left cross section endpoint lat-long (° ' ")	Right cross section endpoint lat-long (° ' ")
Aa	4,777.0	Downstream of meander	39 24 42.6 76 33 14.8	39 24 41.1 76 33 13.5
Bb	4,703.0	Upstream of meander	39 24 42.1 76 33 15.8	39 24 42.4 76 33 13.8
Cc	4,563.0	Straight	39 24 41.1 76 33 16.7	39 24 40.4 76 33 14.5
Dd	4,399.0	Downstream of meander	39 24 40.2 76 33 18.0	39 24 39.0 76 33 17.0
Ee	4,210.0	Upstream of meander	39 24 38.8 76 33 19.6	39 24 38.5 76 33 18.8
Ff	3,990.0	Straight	39 24 37.8 76 33 20.4	39 24 36.5 76 33 19.4
Gg	3,838.0	Straight	39 24 37.0 76 33 22.3	39 24 36.3 76 33 21.3
Hh	3,678.0	Downstream of meander	39 24 35.8 76 33 24.0	39 24 35.1 76 33 23.3
Ii	3,462.0	Between two meanders	39 24 35.3 76 33 25.8	39 24 34.6 76 33 26.1

Bed-Elevation Measurements

Net changes in bed elevation were determined over time at three locations in the study reach where instream piezometers had been installed to monitor shallow ground water (Mayer and others, 2003). These locations closely coincide with locations of permanent cross sections Ee, Ff, and Gg (fig. 6). The distance from the top of the piezometer to the channel bed was measured every 1–2 months and after major storm events between December 2002 and July 2004. Since the measuring point elevations were surveyed and related to mean sea level datum, net bed elevations could be determined over time at the piezometer location by making these periodic measurements. The tracking of bed elevations by use of an instream piezometer with a surveyed measuring point elevation is illustrated in figure 12.

High-Water Marks

High-water marks were obtained along the study reach during water years 2002 through 2004 from **crest-stage gages** that were installed at selected locations (Buchanan and Somers, 1968). These marks were used along with data from the continuous-record streamflow-gaging station to determine peak water-surface elevations that occurred in the study reach between site visits. The crest-stage gages were serviced every 1–2 months and after major storm events. All high-water marks that were registered on each crest-stage gage were documented and logged. The hydrographs from the continuous-record streamflow-gaging station were referenced to determine the date of the storm that left the high-water mark and the discharge associated with that storm.

The distance between crest-stage gages along the thalweg of the stream channel was measured so that water-surface slopes could be determined at a range of stages and discharges by use of the high-water marks. Since the reach in the vicinity of the streamflow-gaging station was the most linear section of the study reach, the streamflow-gaging station and the crest-stage gage immediately downstream of this station were predominantly used for determination of water-surface slopes. A crest-stage gage that was used for obtaining high-water marks in the Minebank Run study reach is shown in figure 13.

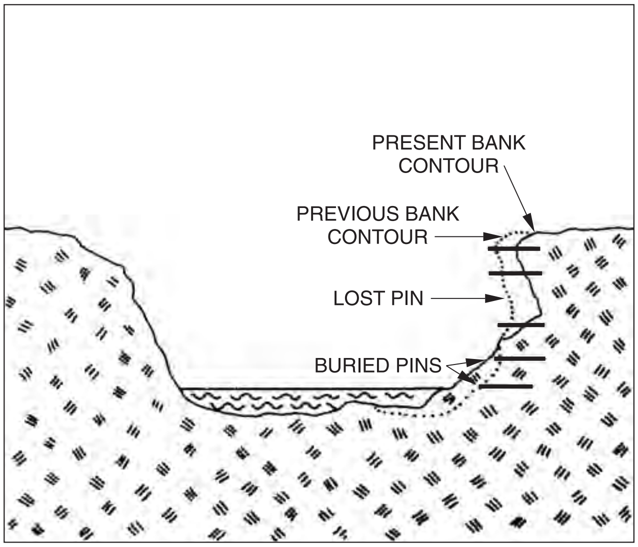

Figure 7. Example of bank-erosion pin placement and monitoring (modified from Harrelson and others, 1994).

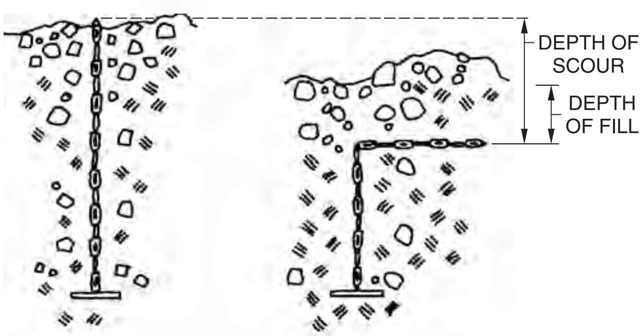

Figure 8. Example of scour chain placement and monitoring (modified from Harrelson and others, 1994).

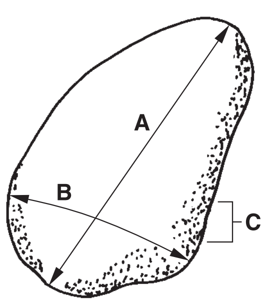

Figure 9. Examples of longest, intermediate, and shortest axes for measuring median particle diameter of pebbles during pebble counts (modified from Harrelson and others, 1994).

Geomorphic Characteristics

Geomorphic data collected during water years 2002 through 2004 were used to assess pre-restoration geomorphic characteristics and pre-restoration geomorphic changes occurring over time in the Minebank Run study reach. Geomorphic characteristics that were assessed included (1) longitudinal profiles of the channel bed, water surface, and bank features; (2) changes in cross-section geometry; (3) grain-size analyses of the channel bed and banks; (4) net changes in the elevation of the channel bed at selected locations over time; (5) classification of selected sections of the reach according to the Rosgen system of stream classification (Rosgen, 1994, 1996); and (6) analysis of boundary shear stress based on cross-section geometry and water-surface slope in the vicinity of the streamflow-gaging station.

Longitudinal Profiles

Longitudinal profiles of the channel bed, water surface, point bar, terrace, and top of bank elevations were developed for the Minebank Run study reach on the basis of field surveys that were conducted in April 2002, April 2003, and April 2004. Slopes of the different channel features were determined by use of simple linear regression. Percentages of riffles, pools, and runs were determined for each profile based on the stream length of each feature relative to the length of the surveyed reach. The profiles also were analyzed to determine differences in the distribution and location of riffles, pools, and runs throughout the study reach over time. An aerial view of the study reach used for the longitudinal surveys is shown in figure 14 (Baltimore County Department of Environmental Protection and Resource Management, 2000). An example plot of the longitudinal profile that was developed from the March 31–April 1, 2003 survey is shown in figure 15.

A distinct and extensive series of point bar and terrace features in the main channel along the study reach is shown in figure 15. The presence of these features indicates that the channel bed has degraded over time and that the stream channel may have abandoned its flood plain at least twice due to degradation. The field evidence indicates that the stream channel may have initially degraded from the top of the topographic banks to form a new flood plain at the level of the terrace feature that was surveyed throughout the study reach. Additional degradation likely caused the stream channel to abandon this flood plain and establish an active flood plain at the approximate elevation of the top of point bar features that were surveyed throughout the study reach.

Slopes were computed for the channel bed, water surface, point bar surface, terrace, and **top of topographic bank** elevations for each of the three longitudinal profiles surveyed between April 2002 and April 2004. The results are shown in table 5.

Table 4. Grain-size distribution and computation of percent finer from pebble count at Cross Section Ff, Minebank Run study reach, June 6, 2003.

[mm, millimeter; %, percent; --, not applicable]

Particle description	Particle size limit (mm)	Item count	Cumulative percent finer (%)
Silt	0.062	0	0
Sand	2	18	18.0
Very fine gravel	4	0	18.0
Fine gravel	8	2	20.0
Medium gravel	16	12	32.0
Coarse gravel	32	14	46.0
Very coarse gravel	64	22	68.0
Small cobbles	128	20	88.0
Large cobbles	256	12	100.0
Small boulders	512	0	100.0
Medium boulders	1,024	0	100.0
Large boulders	2,048	0	100.0
Very large boulders	4,096	0	100.0
TOTAL	--	100	--

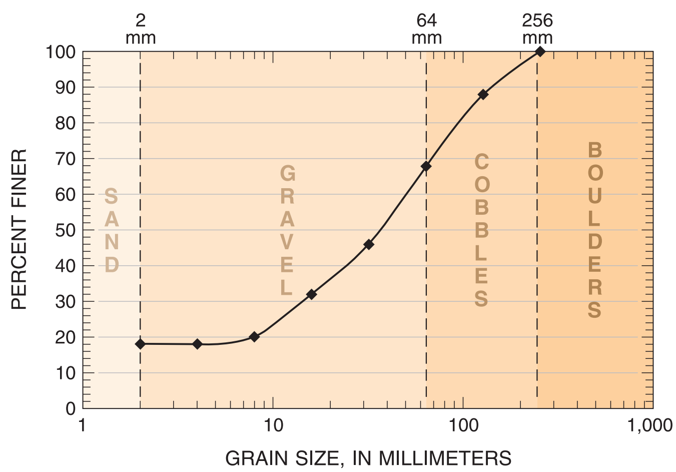

Figure 10. Plot of grain-size distribution developed from the pebble count at cross section Ff, Minebank Run study reach, June 6, 2003.

Slopes for all channel features were approximately 1 percent (table 5). Except for the top of bank slope, all channel features showed a slight decrease in slope between 2002 and 2003, and a slight increase between 2003 and 2004. Over the 2-year period, the slopes of all features showed changes that were within 10 percent or less. A small amount of variation in these numbers was expected, however, due to inherent inaccuracies associated with conventional surveying. The slope of the point bar surface showed the most variation in the re-surveys, likely because the point bars are within the active flood plain and subject to frequent adjustments from higher flows (fig. 16). The slopes of these channel features also are consistent with low-flow and high-flow water-surface slopes that were determined in the Minebank Run study reach from staff gage readings and high-water marks between January 2002 and August 2004 (Doheny and others, 2006).

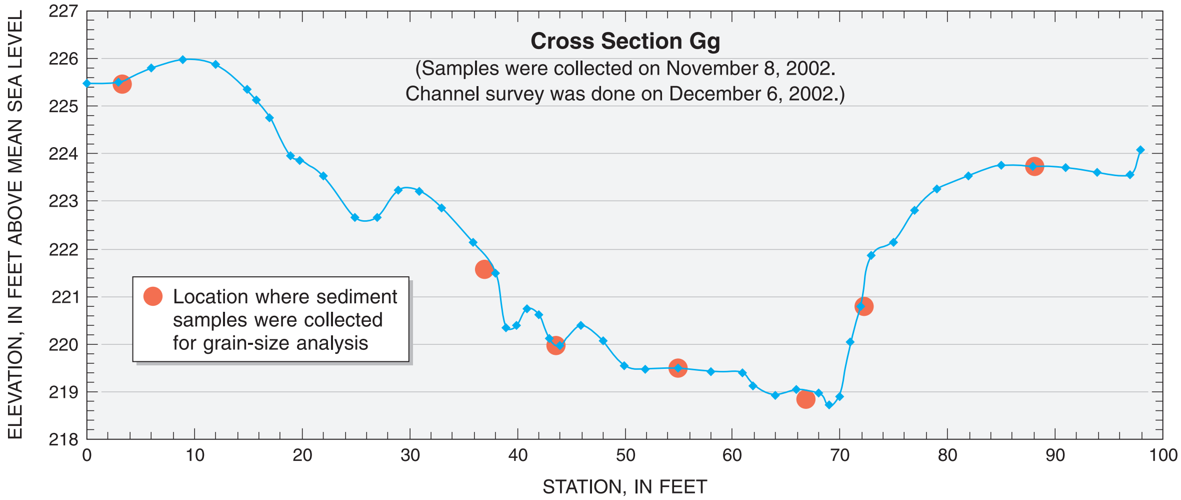

Figure 11. Example of locations within cross section Gg that were selected for sediment-sample collection, Minebank Run study reach, November 2002.

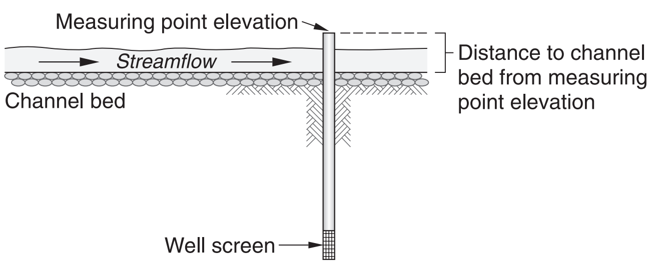

Figure 12. Technique used for tracking of net channel-bed elevations by use of instream piezometers, Minebank Run study reach, December 2002 through July 2004.

Figure 13. Crest-stage gage for obtaining high-water marks in the Minebank Run study reach. (Photograph by Edward J. Doheny, U.S. Geological Survey.)

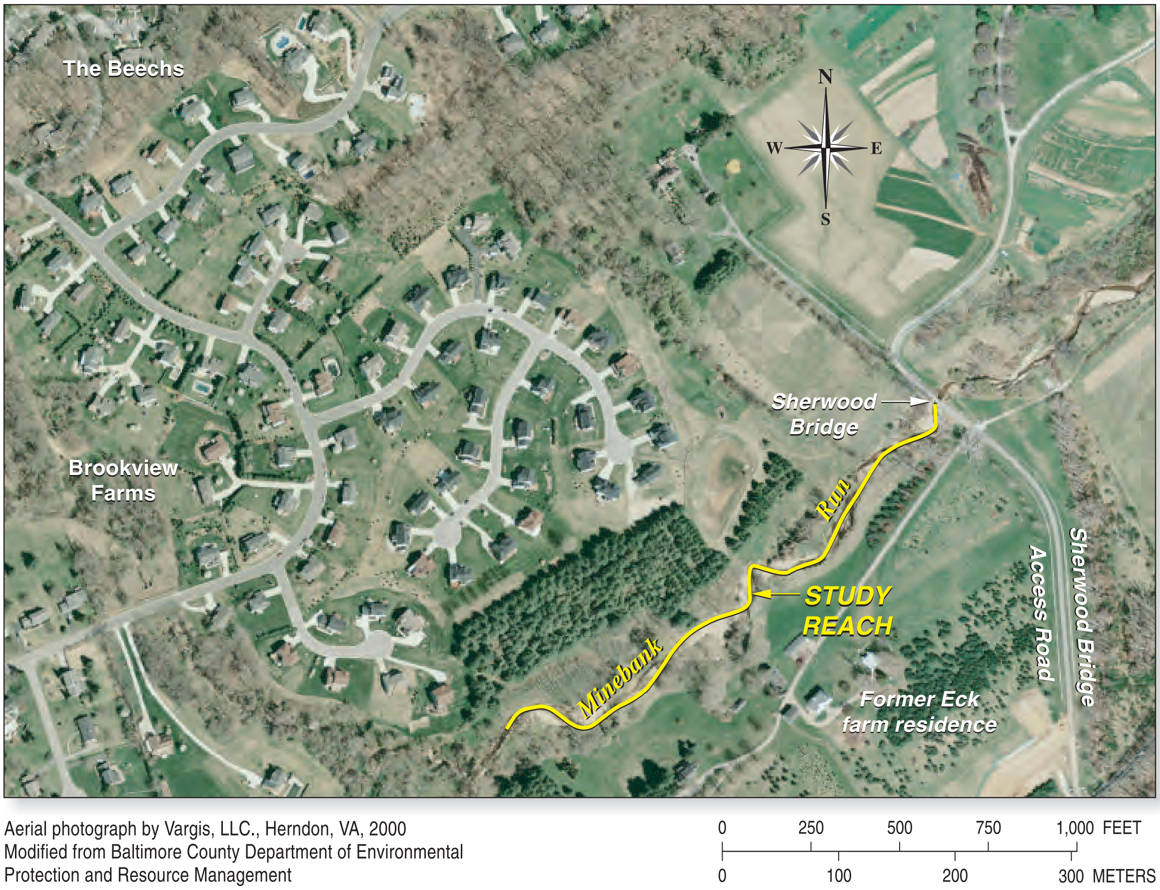

Figure 14. Aerial photograph of Minebank Run study reach in Cromwell Valley Park prior to channel restoration.

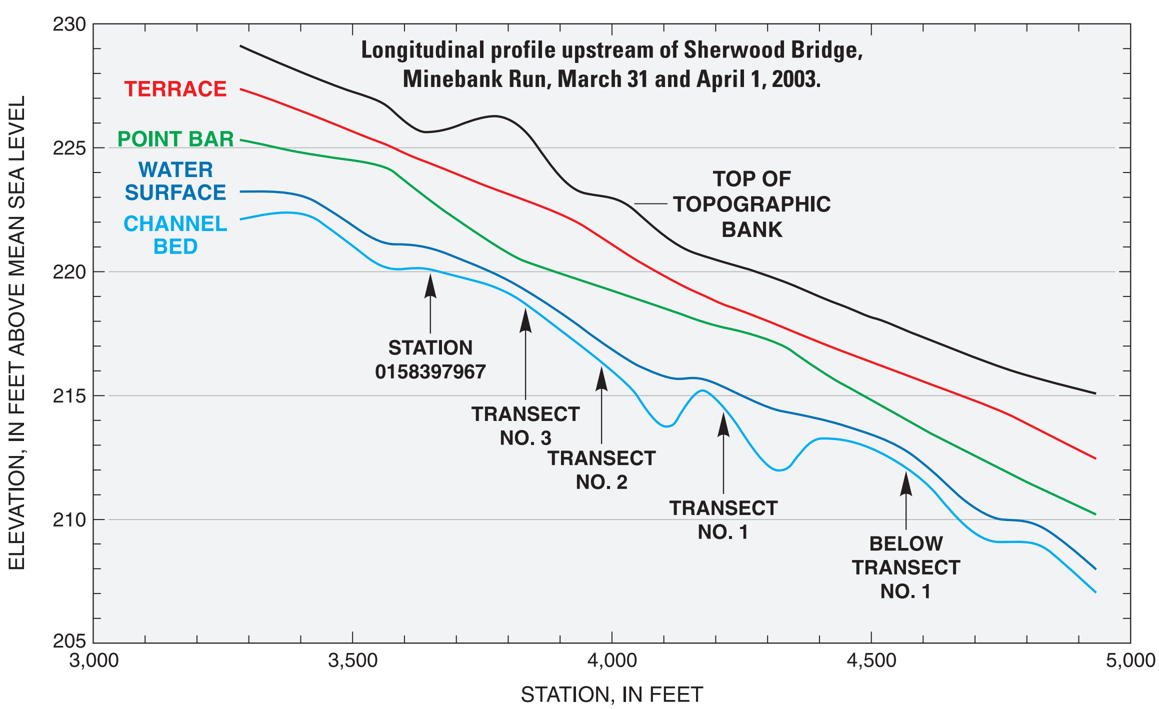

Figure 15. Longitudinal profile of channel features in the Minebank Run study reach from field survey conducted on March 31 and April 1, 2003.

Table 5. Slopes of channel features in the Minebank Run study reach from longitudinal-profile surveys, 2002–04.

Date of survey	Channel bed	Water surface	Point bar surface	Terrace surface	Top of bank
April 16, 2002	0.0101	0.0100	0.0101	0.0099	0.0091
March 31–April 1, 2003	0.0093	0.0092	0.0092	0.0091	0.0089
April 23, 2004	0.0095	0.0095	0.0107	0.0097	0.0088

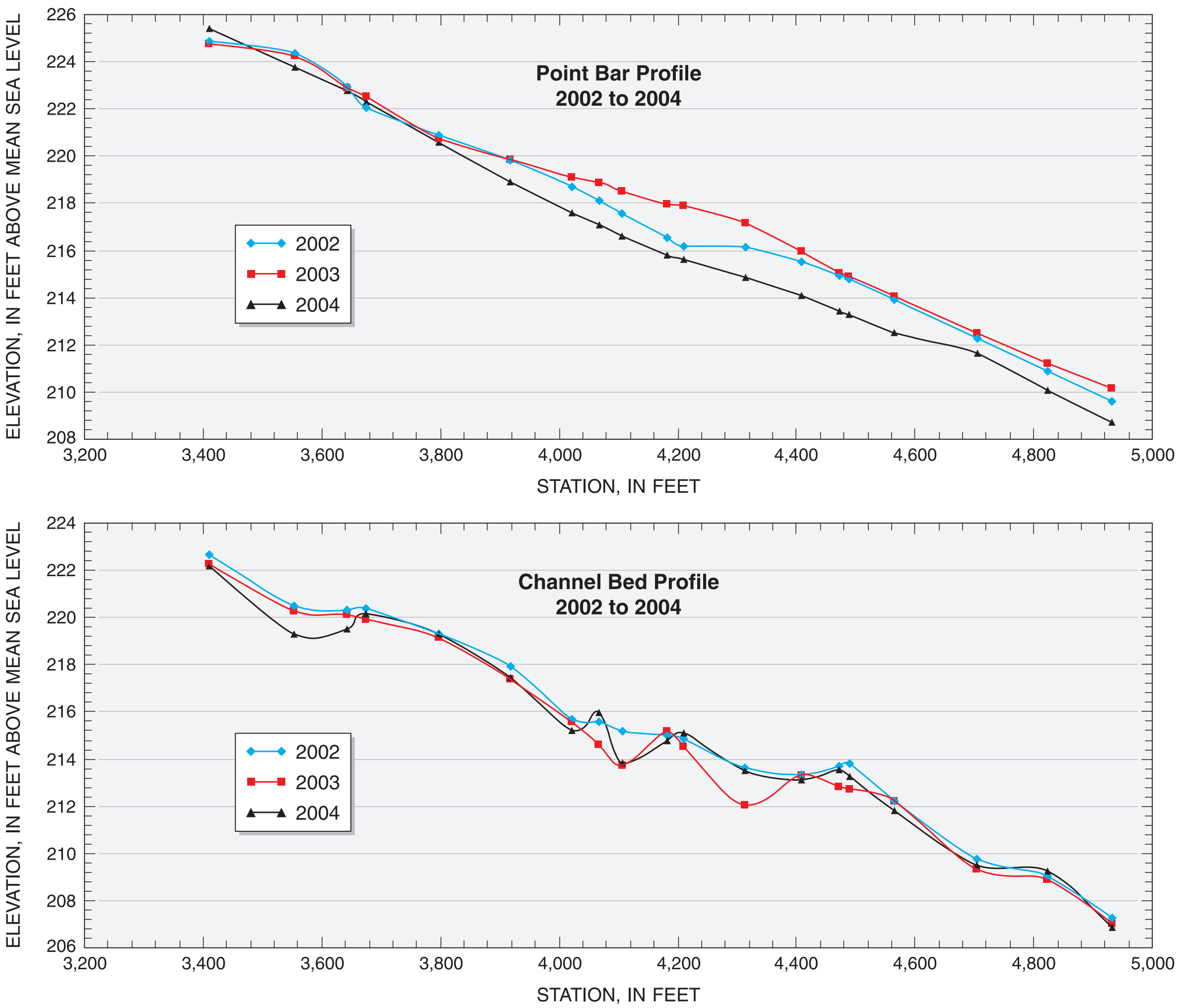

Figure 16. Variation in point bar and channel bed elevation between 2002 and 2004 longitudinal surveys in the Minebank Run study reach.

The data indicate that despite major geomorphic changes to the stream channel from storms, the overall slope of the channel bed and other channel features remained at about 1 percent.

Data from the longitudinal-profile surveys also were used to determine the percentages of riffles, pools, and runs in the study reach and whether these percentages and distribution remain consistent over time. The percentages of riffles, pools, and runs in the Minebank Run study reach that were determined from the longitudinal-profile surveys between 2002 and 2004 are shown in table 6. The distribution of riffles, pools, and runs that were determined from the longitudinal-profile surveys between 2002 and 2004 are shown in figure 17.

Noticeable changes are evident in the percentages of riffles, pools, and runs in the study reach between April 2002 and April 2004 (table 6). The large changes in percentages of pools over time indicate that different sections of the stream channel go through alternating periods of scour and fill over time. The increase in riffle and run percentages with the corresponding decrease in pool percentages between 2002 and 2003 indicates that, on average, the channel in the study reach is storing more sediment during this period. The increase in pool percentages and corresponding decrease in run percentages between 2003 and 2004 indicates that, on average, the channel in the study reach is storing less sediment during this period. Some distinct variations in the distribution and location of riffles, pools, and runs in many sections of the study reach are also evident (fig. 17). Despite these changes in riffle, pool, and run percentages and changes in the distribution and location of these features, this analysis indicated that, on average, the stream is roughly maintaining the overall slope of its channel features.

Table 6. Percentage of riffles, pools, and runs in the Minebank Run study reach from longitudinal-profile surveys, 2002–04.

[%, percent]

Date of survey	Riffle (%)	Pool (%)	Run (%)
April 16, 2002	42.2	42.3	15.5
March 31–April 1, 2003	52.2	27.5	20.3
April 23, 2004	52.4	39.9	7.7

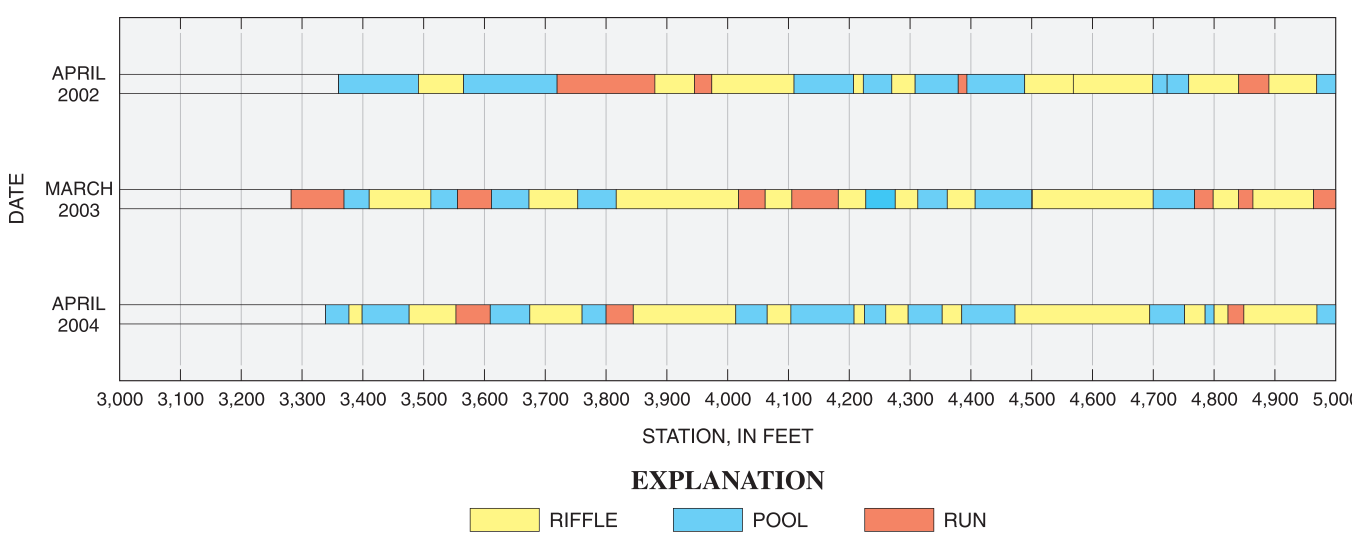

Figure 17. Comparison of riffle, pool, and run distribution in the Minebank Run study reach prior to channel restoration, 2002 through 2004.

Cross-Section Geometry

Pre-restoration channel geometry at the nine permanent cross sections was determined on the basis of field surveys conducted in December 2002, June-July 2003, and in January-February 2004. Each cross section was plotted for the three surveys to determine changes in bed elevation and channel alignment over time. Bank-pin data collected in locations with cut banks were used to investigate bank retreat. Data collected from the scour chains were used to measure, or reasonably approximate, depths of maximum scour as well as depths of deposition that occurred on the recession of storm events. Cross-sectional area, **wetted perimeter**, **hydraulic radius**, channel width, and mean channel depth were determined for each cross section at a range of water-surface elevations, and compared to document changes occurring between field surveys.

Plots of the nine permanent cross sections are shown in figures 18–26. Varying degrees of aggradation and degradation of the channel bed are evident, as well as lateral erosion along the study reach. A summary of lateral erosion, maximum scour, and depths of maximum deposition that were directly measured, or reasonably approximated, based on field conditions during site visits at or near each permanent cross section in the study reach during the pre-restoration period is provided in table 7.

Data from the bank-pin measurements, as well as measurements made after bank collapses in some of the cross-section locations, indicate a range of 0.21 to 7.88 ft of lateral erosion from January 2003 through August 2004. Individual bank-pin measurements during site visits indicate that lateral bank erosion of 1–2 ft was possible during large storm events that occurred from January 2003 through July 2004. Data from scour chains at the cross sections indicate that maximum bed scour ranging from 0.1 to 1.4 ft was possible in the thalweg of the channel during large storm events occurring between January 2003 and July 2004. Maximum deposition on the channel bed at the location of the scour chains ranged from approximately 0.30 to 1.50 ft. Due to the dynamic and unstable nature of the unrestored channel at Minebank Run, scour chains and bank pins were sometimes lost during large storm events. When this occurred, estimates of bank retreat and maximum scour were made on the basis of known conditions from the previous site visit. If a known length of a bank pin or a scour chain was exposed during a site visit, for example, and the total length of the pin or chain was known, a rough estimate of erosion on the bank or bed could be made if the pin or chain was washed away during a storm event prior to the next site visit. Data from the resurveyed cross sections were also used to aid in estimating bank retreat during periods when bank pins had been lost.

Cross-section geometry was determined at a range of stages for the three different field surveys at all nine permanent cross-section locations. Hydraulic variables that were determined include cross-sectional area, wetted perimeter, hydraulic radius, channel width, and mean channel depth. A comparison of cross-section geometry for cross-section Hh during the three field surveys conducted during 2002 through 2004 is shown in table 8. Comparisons for each of the other eight permanent cross sections in the Minebank Run study reach are included in Appendix 1.

A net increase in cross-sectional area, hydraulic radius, and mean depth over time is evident at cross-section Hh (table 8). Channel width and wetted perimeter show net increases at low- to mid-range water-surface elevations over time. These changes in channel width occur mainly within the active channel, due to the net effects of erosion and deposition of the point bar on the right side of the channel. At higher elevations, the channel width did not change significantly over time. The cross-section surveys also indicate alternating increases and decreases in cross-sectional area and mean depth between field surveys, which indicates alternating aggradation and degradation of the channel bed resulting from temporary storage and removal of sand and gravel during storm events.

These analyses were performed for all permanent cross sections in the Minebank Run study reach, and were used to develop an overall assessment of channel geometry changes in the study reach that occurred between 2002 and 2004. The results are summarized in table 9.

Net increases in cross-sectional area, channel width, and mean depth for most elevations at cross sections Aa, Dd, Ff, and Ii are indicated in table 9. These changes indicate an overall trend of bed degradation, bank instability, and channel widening over time. Cross section Aa, however, shows alternating increases and decreases in mean depth between field surveys. This indicates that, like cross section Hh, sand and gravel could be temporarily stored in this location after certain storm events despite overall degradation during the monitoring period. Considerable lateral bank erosion is also a likely factor in the increases in cross-sectional area and channel width at these locations.

A net decrease in cross-sectional area and mean depth over time at cross section Bb is evident (table 9). Channel width shows a net decrease at lower elevations, with relatively minor increases and decreases at higher elevations. The surveys and bank pin information also indicate that lateral erosion was relatively minor over time. The decrease in cross-sectional area and mean depth with little lateral erosion indicates an aggrading channel bed at cross section Bb with a net increase in storage of sediment that is transported during storm events.

Cross section Cc shows approximately the same channel-geometry characteristics that were documented at cross section Hh. The cross-sectional surveys indicate a net increase in cross-sectional area, hydraulic radius, and mean depth over time. Channel width shows a net increase at lower to mid-range elevations over time. These changes in channel width occur mainly within the active channel, due to the net effects of erosion at the base of the terrace on the left side of the channel. At most higher elevations, the channel width did not change considerably over time. The cross-section surveys also indicate alternating increases and decreases in cross-

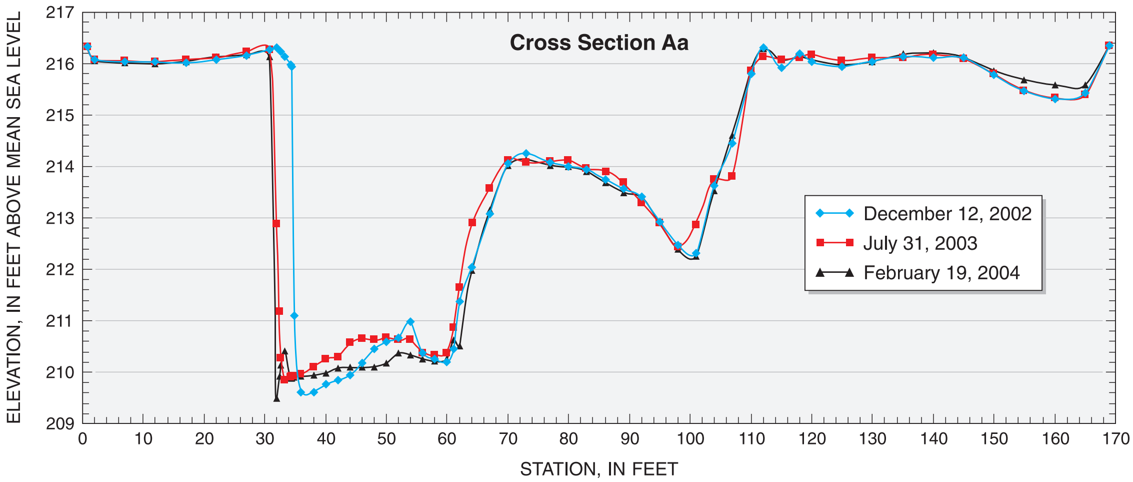

Figure 18. Pre-restoration cross-section geometry at permanent cross section Aa, December 2002 through February 2004.

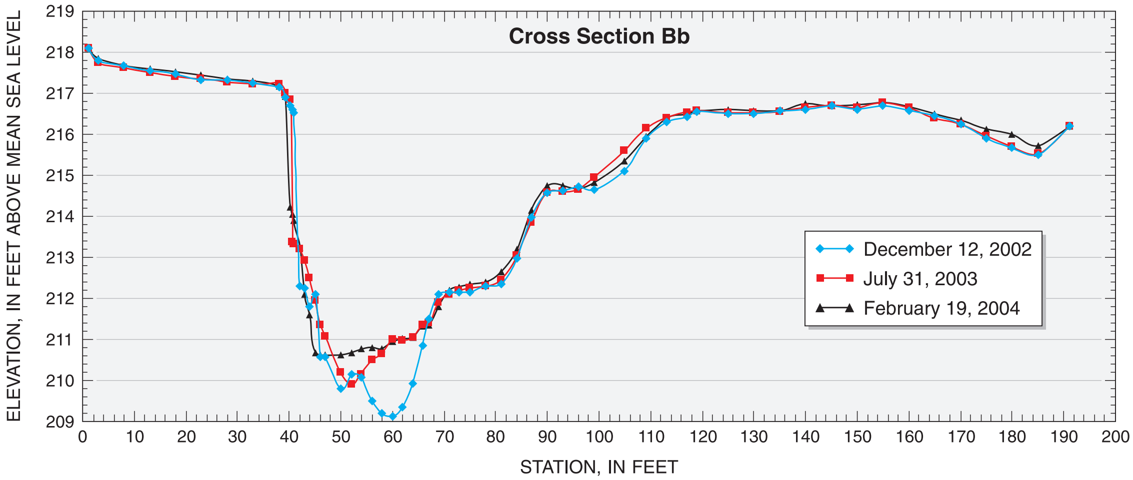

Figure 19. Pre-restoration cross-section geometry at permanent cross section Bb, December 2002 through February 2004.

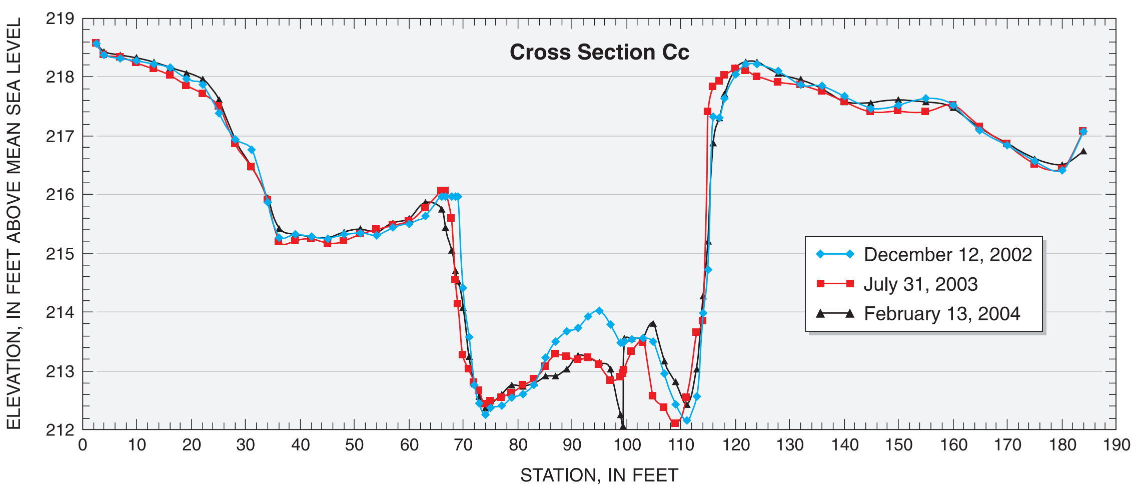

Figure 20. Pre-restoration cross-section geometry at permanent cross section Cc, December 2002 through February 2004.

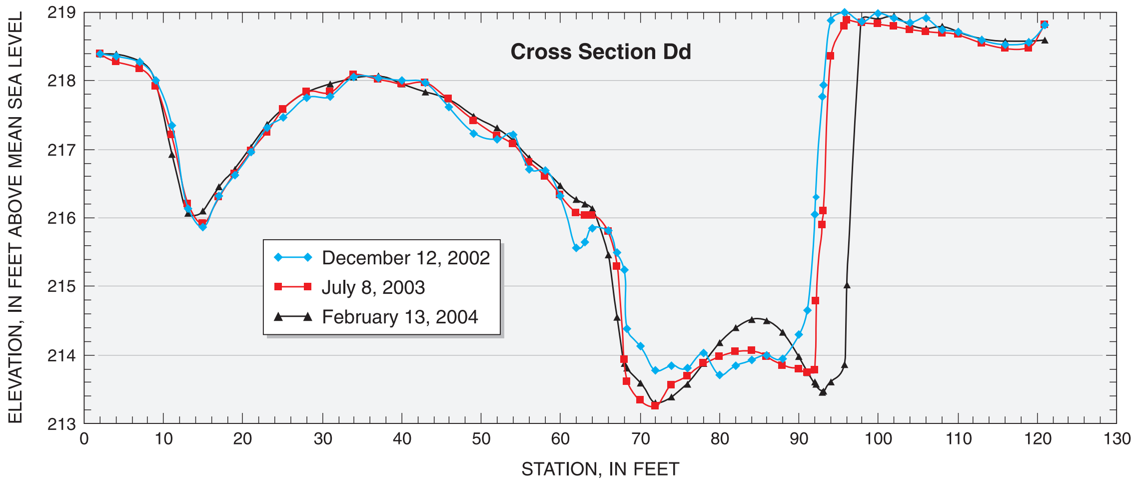

Figure 21. Pre-restoration cross-section geometry at permanent cross section Dd, December 2002 through February 2004.

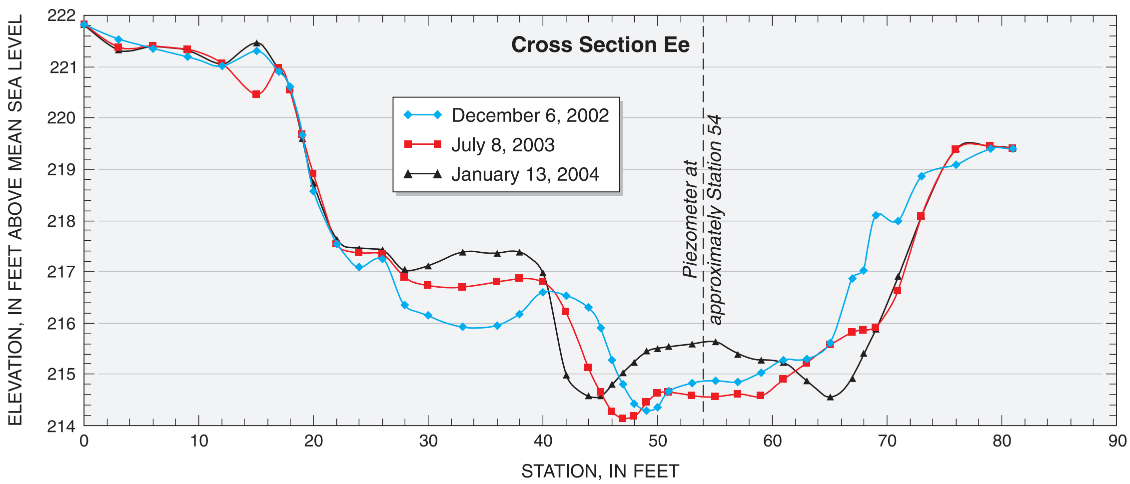

Figure 22. Pre-restoration cross-section geometry at permanent cross section Ee, December 2002 through January 2004.

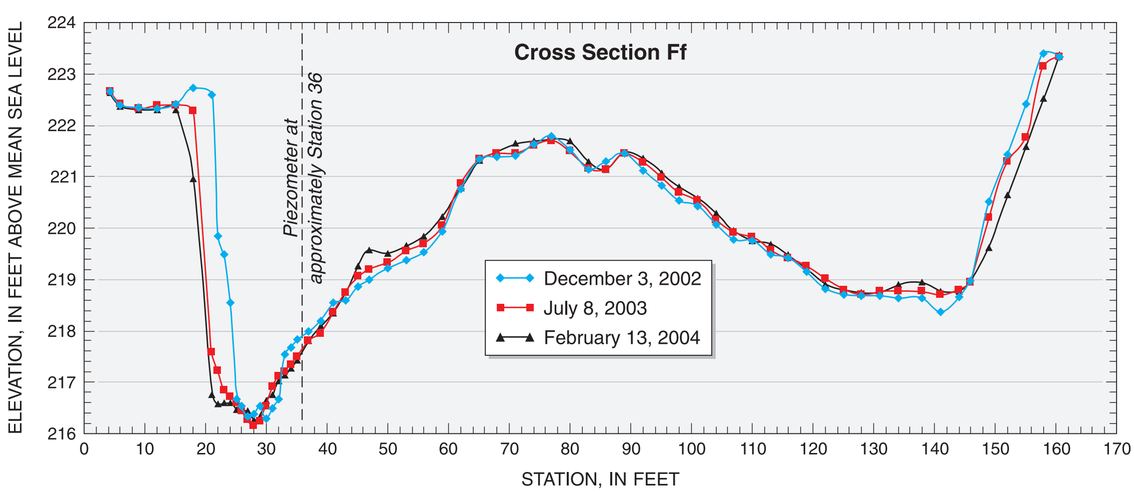

Figure 23. Pre-restoration cross-section geometry at permanent cross section Ff, December 2002 through February 2004.

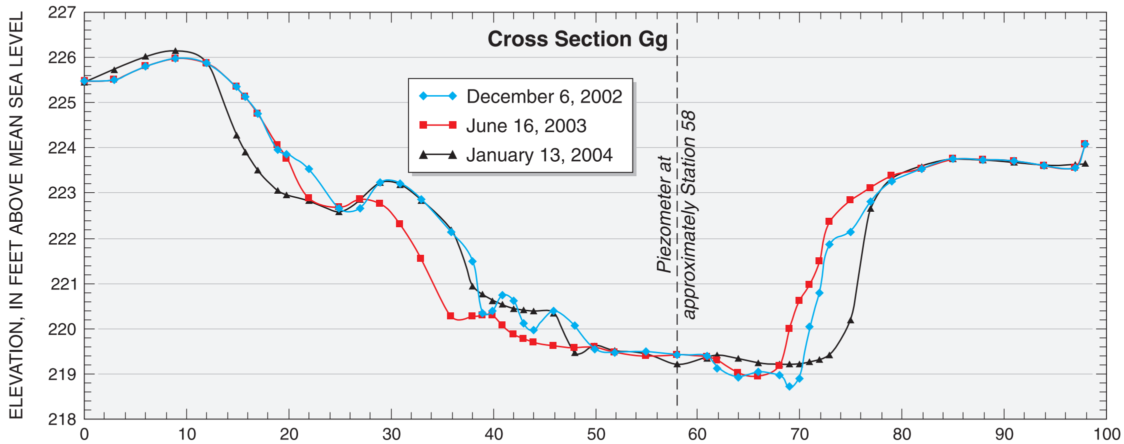

Figure 24. Pre-restoration cross-section geometry at permanent cross section Gg, December 2002 through January 2004.

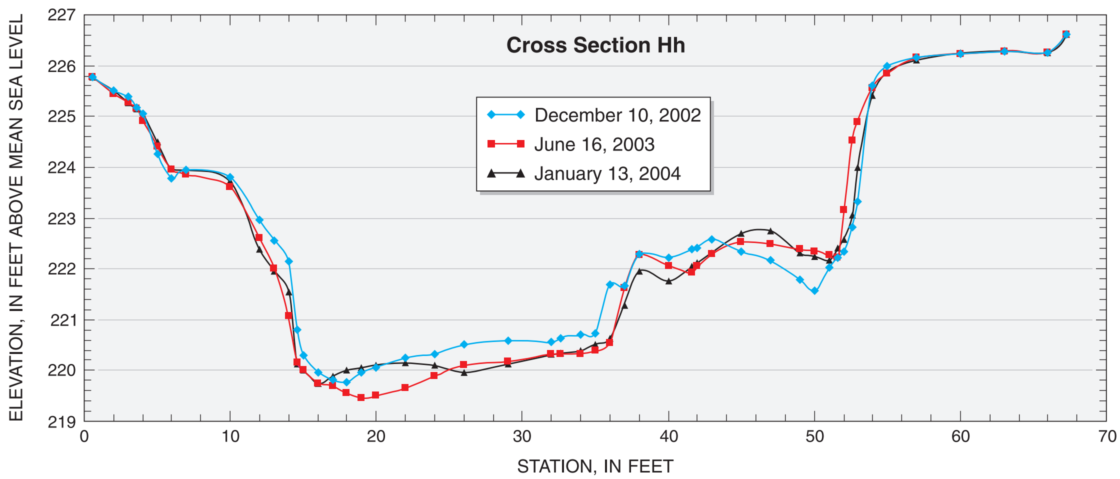

Figure 25. Pre-restoration cross-section geometry at permanent cross section Hh, December 2002 through January 2004.

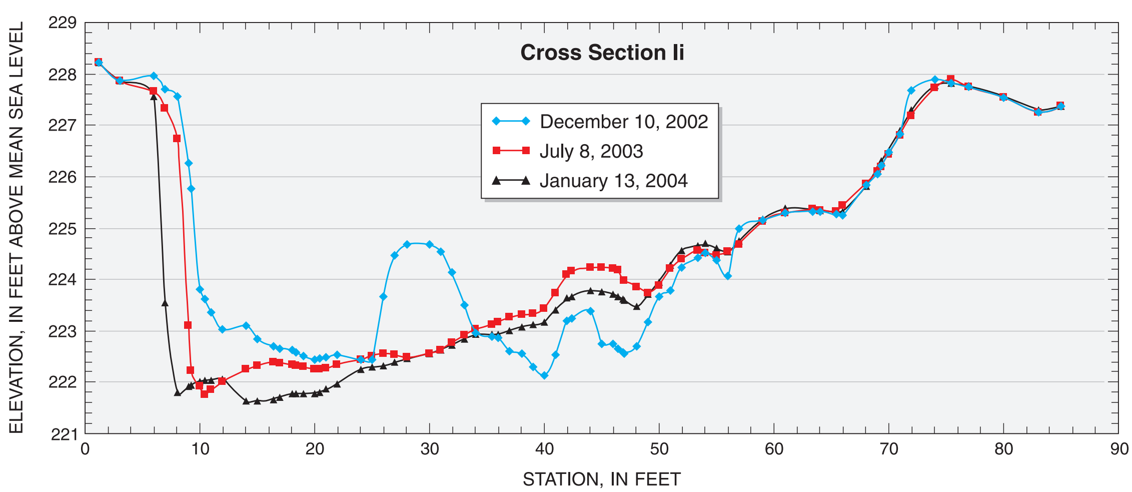

Figure 26. Pre-restoration cross-section geometry at permanent cross section Ii, December 2002 through January 2004.

Table 7. Approximate extent of lateral erosion, maximum scour, and maximum depths of deposition for each permanent cross section in the Minebank Run study reach, 2003–04.

[e = includes estimates due to loss of pins from bank collapse or loss of scour chain during large storm event.]

Cross section	Period of bank pin monitoring (month/year)	Total lateral erosion of cut bank (feet)	Period of scour chain monitoring (month/year)	Maximum scour depth between site visits (feet)	Maximum bed deposition between site visits (feet)
Aa	1/2003–8/2004	3.71e	2/2003–12/2003	0.60	1.50e
Bb	1/2003–7/2004	0.95	2/2003–6/2004	1.19e	0.50
Cc	1/2003–7/2004	0.83	2/2003–7/2004	0.10	0.60
Dd	1/2003–7/2004	7.88e	2/2003–6/2004	1.44e	0.80e
Ee	1/2003–7/2004	0.61[1]	2/2003–12/2003	1.22e	0.96e
Ff	1/2003–12/2003	4.86e	2/2003–12/2003	0.40e	0.60
Gg	1/2003–12/2003	4.68e	2/2003–6/2004	1.00e	0.30
Hh	1/2003–7/2004	0.21	2/2003–12/2003	0.42	0.60
Ii	1/2003–7/2004	4.96e	2/2003–6/2004	0.88e	1.25

[1] Lateral erosion for cross section Ee was measured along the left bank, approximately 25 feet downstream of the cross-section location because of a nearby meander bend.

sectional area and mean depth between field surveys. As with cross section Hh, this condition indicates temporary storage and removal of sand and gravel during storm events with net degradation of the channel bed over time.

Cross-section Ee shows a net increase in cross-sectional area at lower elevations and a net decrease at higher elevations. Mean depth shows a net decrease at most elevations, but alternates between increasing depth and decreasing depth between channel surveys. Changes in channel width are considerable and vary between increases and decreases over the range of elevations analyzed. The cross-section surveys indicate major vertical and lateral instability of the stream channel in this location, with alternating periods of considerable sediment storage and removal.

Cross section Gg shows net increases in cross-sectional area and channel width over time. Mean depths show a small net decrease at lower elevations, and a net increase at higher elevations. The cross-section surveys indicate greater lateral instability of the stream channel than vertical instability in this location. Lateral migration of the right bank, and adjustment of the terrace and point bar features on the left side of the channel are the main cause of the net increases in cross-sectional area and mean depth over time.

A summary of the pre-restoration geomorphic conditions that were interpreted from changes in the cross sections during the monitoring period is shown in figure 27. Cross sections Bb and Ee appear to be primary areas for sediment storage within the study reach. Cross section Ee appears to store large volumes of sediment for short periods of time and is vertically and laterally unstable. Cross section Bb shows net aggradation of the channel bed over time with small amounts of lateral erosion. Cross sections Aa, Cc, and Hh also show indications of temporary sediment storage and removal over time. Cross sections Aa, Dd, Ee, Ff, and Ii appear to be the most unstable cross sections in the study reach, due to either considerable lateral erosion, erosion of the channel bed, or both. Cross section Gg appears to be laterally unstable with a lesser degree of vertical instability. On the basis of the locations of cut banks and lateral erosion in the study reach, the stream channel was actively adjusting its meander pattern and trying to increase its **sinuosit**y prior to restoration.

Grain-Size Analysis

Grain-size distributions were determined for sediment in the channel bed and banks in the study reach during 2002 and 2003 by use of (1) pebble counts of the surficial channel-bed sediments at each cross section (Wolman, 1954), and (2) sediment samples that were collected from the channel banks and the subsurface of the channel bed at each cross section. Cumulative frequency distributions of percent finer were developed for the surficial bed material based on the pebble count data. The median particle diameter, or particle diameter associated with 50 percent of the material being finer, was determined for each pebble count and sample location. Grain-size distributions from the pebble counts also were combined to develop a composite analysis of the surficial bed material for the entire study reach. The 2003 grain-size distributions also were compared to selected pebble counts

Table 8. Changes in cross-section geometry at permanent cross-section Hh, Minebank Run study reach, 2002 through 2004.

[ft, feet; ft^2, square feet; Hyd., Hydraulic; %, percent]

Elevation	Cross-sectional area (ft^2)	Cross-sectional area (ft^2)	Cross-sectional area (ft^2)	Wetted perimeter (ft)	Wetted perimeter (ft)	Wetted perimeter (ft)	Hyd. radius (ft)	Hyd. radius (ft)	Hyd. radius (ft)	Channel width (ft)	Channel width (ft)	Channel width (ft)	Mean channel depth (ft)	Mean channel depth (ft)	Mean channel depth (ft)
Ft above mean sea level	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
222.00	35.3	45.3 (+28.3%)	43.2 (+22.4%)	25.1	26.0	30.3	1.41	1.74	1.42	23.5	24.3	28.5	1.50	1.86	1.52
222.50	48.2	60.0 (+24.5%)	58.4 (+21.2%)	31.2	34.3	34.1	1.54	1.75	1.71	29.4	32.2	32.1	1.64	1.86	1.82
223.00	71.7	80.6 (+12.4%)	78.8 (+9.9%)	43.3	43.3	44.0	1.66	1.86	1.79	40.8	40.6	41.5	1.76	1.99	1.90
223.50	92.5	101.1 (+9.3%)	99.8 (+7.9%)	45.2	44.9	45.4	2.05	2.25	2.20	42.4	41.7	42.5	2.18	2.42	2.35
224.00	114.5	122.8 (+7.2%)	121.6 (+6.2%)	51.1	50.2	50.4	2.24	2.45	2.41	47.8	46.5	47.0	2.40	2.64	2.58
224.50	138.7	146.4 (+5.6%)	145.4 (+4.8%)	52.6	51.9	52.0	2.64	2.82	2.79	48.8	47.8	48.2	2.84	3.06	3.02
225.00	163.3	170.6 (+4.5%)	169.7 (+3.9%)	53.9	53.7	53.6	3.03	3.18	3.16	49.7	49.2	49.3	3.29	3.46	3.44
225.50	188.5	195.8 (+3.9%)	195.0 (+3.4%)	56.6	56.8	56.7	3.33	3.45	3.44	51.9	52.1	52.1	3.63	3.76	3.74
225.78	203.3	210.7 (+3.6%)	210.0 (+3.3%)	58.7	58.9	58.9	3.47	3.58	3.56	53.9	54.2	54.2	3.78	3.89	3.88

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Table 9. Summary of variability of cross-sectional characteristics in the Minebank Run study reach, 2002 through 2004.

Cross section	Lateral erosion	Cross-sectional area	Channel width	Mean channel depth	Comments
Aa	Considerable on left bank	Net increase	Net increase	Net increase	Considerable lateral and vertical changes in section. Channel migrating to left side of valley.
Bb	Slight on left bank	Net decrease	Slight increases and decreases at range of elevations.	Net decrease at most elevations.	Small lateral changes in section. Channel bed aggrading over time.
Cc	Some on base of left terrace	Net increase	Slight increase in main channel at lower elevations. Slight decrease at higher elevations.	Net increase at most elevations.	Considerable vertical changes in section. Some lateral adjustment of left bank terrace. Overall, lateral location of section is maintained over time.
Dd	Considerable on right bank	Net increase	Net increase	Net increase	Considerable lateral/vertical changes in section. Channel migrating to right side of valley.
Ee	Considerable on right bank	Increasing from 2002 to 2003. Decreasing from 2003 to 2004. Net increase at lower elevations. Net decrease at higher elevations.	Net increase at most elevations.	Net decrease at most elevations.	Major lateral and vertical changes in section. Channel migrating to right side of valley.
Ff	Considerable on left bank	Net increase in main channel.	Net increase at most elevations.	Net increase in main channel.	Considerable lateral changes in section. Some vertical changes on channel bed in main channel. Channel migrating to left side of valley.
Gg	Considerable on right bank	Net increase	Net increase at most elevations.	Slight net decrease at lower elevations. Slight net increase at higher elevations.	Significant lateral changes in section. Slight vertical changes on channel bed. Channel migrating to right side of valley.
Hh	Slight on both banks	Increasing from 2002 to 2003. Decreasing from 2003 to 2004. Net increase at most elevations during 2002–04.	Net increase at low elevations. Slight increases and decreases at higher elevations.	Net increase at most elevations.	Considerable vertical changes to channel bed and point bar. Slight lateral changes in section over time.
Ii	Considerable on left bank	Net increase	Net increase	Net increase	Considerable lateral and vertical changes in section. Channel migrating to left side of valley.

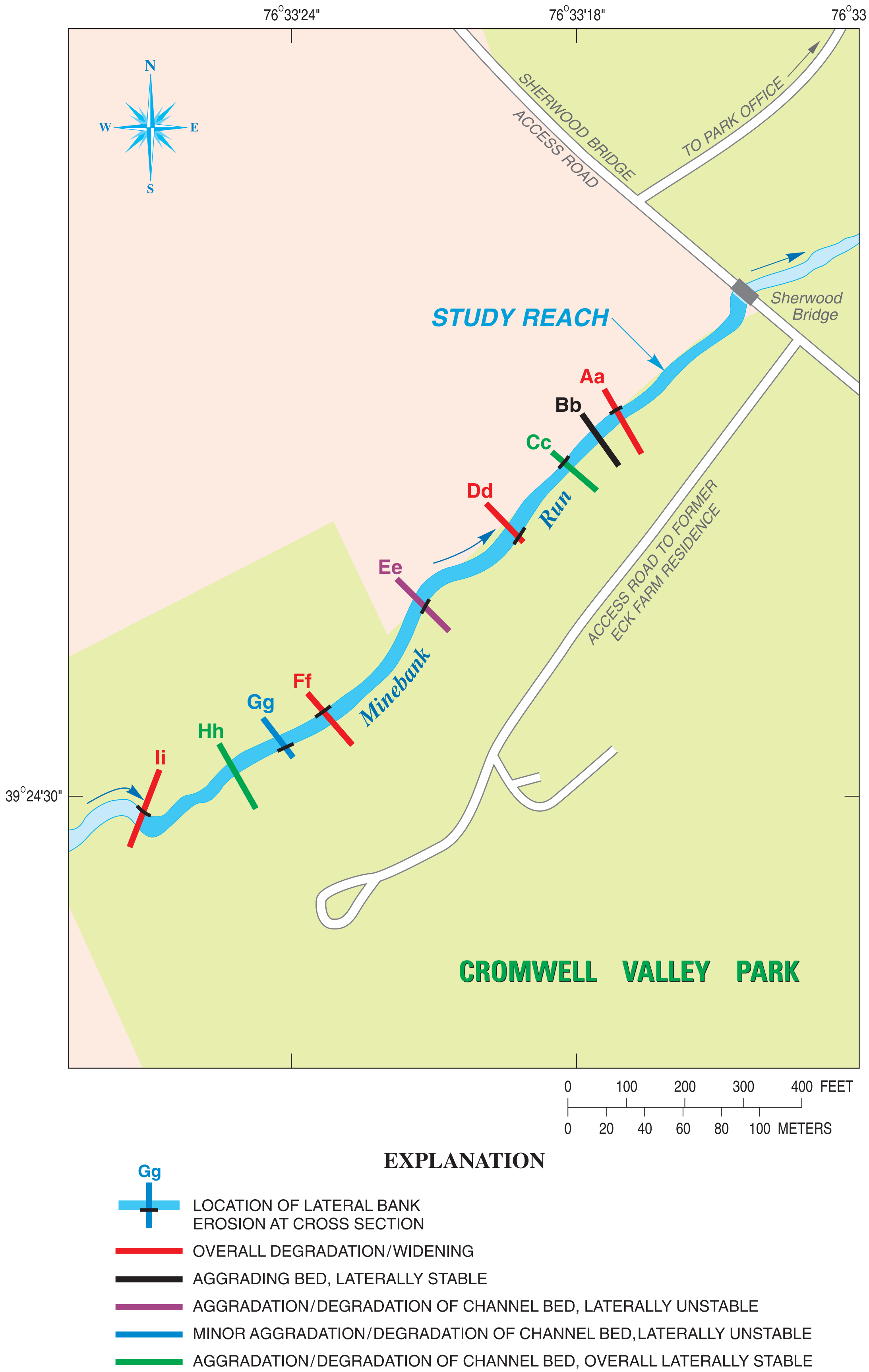

Figure 27. Summary of pre-restoration geomorphic conditions in the Minebank Run study reach, 2002 through 2004.

that were made in 2002 at the three ground-water transect locations, corresponding to permanent cross sections Ee, Ff, and Gg respectively.

Pebble count data that were collected during May and June 2003 were used to develop grain-size distributions of percent finer for the surficial bed material. The distributions were developed for each cross section based on the percentages of counted pebbles that fall within 12 particle-size ranges of sand, gravel, cobbles, and boulders. The results are shown in table 10.

A wide range of grain sizes is present within the Minebank Run study reach (table 10). Several locations in the study reach had considerable percentages of sand, including cross sections Bb, Ee, Gg, Hh, and Ii. Cross sections Gg, Hh, and Ii collectively represent approximately the upper 28 percent of the study reach. Cross sections Bb, Ee, and Ii are located near meanders in the stream channel, which indicates that finer material may be temporarily stored in these locations and transported during storm events. The cross-section geometry at cross section Bb also indicates a net aggradation of the channel bed over time in this location. Cross section Hh, which is in a fairly straight reach, is also a location where finer material can be stored because of a braided sand and gravel bar that was acting as a grade control at the start of the study.

Cross sections Cc, Dd, and Ff had the coarsest distribution of grain sizes, including a higher percentage of gravel and cobbles than the other locations. Cross section Aa had a considerable amount of gravel and some sand, but fewer cobbles. Cross sections Aa, Cc, and Ff are in fairly straight reaches, which indicates that finer material may be transported through these locations during storms with relatively small amounts of net storage. The cross-section geometry at cross sections Aa, Dd, and Ff also indicated lateral erosion of at least one of the channel banks, which may have exposed coarser bed material as the channel migrated. Only a few boulders were present in the entire study reach.

The median particle diameter (d50), or particle diameter associated with 50 percent of the material being finer, was determined for each surficial pebble count and for all bank and subsurface sample locations at each cross section. The results are shown in table 11.

The data listed in table 11 indicate a wide variation of d50 values throughout the study reach. Most sample locations on the banks indicated a d50 in the silt/clay range or in the range of very fine to coarse sand. The subsurface material in the channel bed is coarser than the channel banks in most locations. In cross sections Bb, Cc, Dd, and Ff, parts of the channel subsurface were coarser than the surficial bed material, based on the pebble count data. The subsurface samples also confirmed that cross sections Cc, Dd, and Ff are the coarsest locations in the study reach.

Data from the pebble counts at each of the nine cross sections also were combined to develop a composite grain-size distribution of the surficial bed material for the entire study reach. This distribution was developed using over 900 pebbles that were collected in the cross sections during May and June of 2003. The grain-size distribution and computation of percent finer for the composite pebble count in the Minebank Run study reach is shown in table 12. These results are presented graphically in figure 28.

The data in table 12 show that the majority of particle sizes in the Minebank Run study reach falls between medium gravel and small cobbles. The analysis also indicates that over 24 percent of the pebbles counted throughout the study reach were sand. As shown in figure 28, the d50 for this analysis is approximately 20.5 mm, which falls within the range of coarse gravel. The analysis also indicates that less than 20 percent of the surficial particles were in the cobble range. The abundance of relatively small bed material sizes in combination with the flashy streamflow from urban and suburban runoff likely contributes to the considerable geomorphic changes that have been observed during this investigation (Doheny and others, 2006).

The grain-size distributions that were developed from pebble count data collected in 2003 were compared to distributions from selected pebble counts that were made in 2002 at the three ground-water transect locations, which correspond to permanent cross sections Ee, Ff, and Gg respectively. Grain-size distributions at these locations for 2002 and 2003 are shown in figures 29–31. An overall shift to larger grain-size distributions, or coarsening, can be seen at all three locations between 2002 and 2003. For cross section Ee, the median particle diameter increased from 18 mm in 2002 to 30 mm in 2003. For cross section Ff, the median particle diameter increased from approximately 31.5 mm in 2002 to 36 mm in 2003. For cross section Gg, the median particle diameter increased from 10 mm in 2002 to 14 mm in 2003. For cross section Ee, there was a slight decrease in the percentage of sand particles between 2002 and 2003, whereas there were slight increases in the percentages of sand particles at cross sections Ff and Gg between 2002 and 2003. These data indicate that from May 2002 through June 2003, the changes in grain-size distribution appear to be largely due to changes in the percentages and distribution of gravel on the surface of the channel bed. Coarsening of the channel bed could be the result of large storms that are transporting and re-distributing sand, gravel, and cobbles within the stream channel.

Net Changes in Bed Elevation

Net changes in bed elevation were monitored in selected locations of the study reach by use of the stream piezometers that had been installed for monitoring shallow ground water under the channel bed. The locations of these piezometers correspond very closely to the locations of cross sections Ee, Ff, and Gg. The net changes in bed elevation at these three locations were tracked over a period of about 1.5 years, starting in December 2002 and January 2003, and ending in July 2004. The net changes in bed elevation during this period at these locations are shown in figures 32–34.

Table 10. Cumulative distribution of grain sizes, in percent finer, for surficial bed material at permanent cross section locations in the Minebank Run study reach, 2003.

[Values represent the percentage of total particles that are finer than the particle size indicated in the second column of each row of values. mm, millimeters; %, percent]

Particle description	Particle size limit (mm)	Aa (%)	Bb (%)	Cc (%)	Dd (%)	Ee (%)	Ff (%)	Gg (%)	Hh (%)	Ii (%)
Silt	0.062	0	0	0	0	0	0	0	0	0
Sand	2	11.0	30.0	3.9	4.0	30.0	18.0	25.0	61.4	35.0
Very fine gravel	4	13.0	33.0	3.9	4.0	30.0	18.0	26.0	62.4	36.0
Fine gravel	8	23.0	48.0	6.8	6.0	31.0	20.0	34.0	67.3	45.0
Medium gravel	16	43.0	56.0	17.5	26.0	36.0	32.0	52.0	78.2	59.0
Coarse gravel	32	61.0	64.0	29.1	46.0	51.0	46.0	68.0	86.1	76.0
Very coarse gravel	64	86.0	80.0	61.2	74.0	80.0	68.0	88.0	97.0	91.0
Small cobbles	128	99.0	97.0	87.4	94.0	100.0	88.0	99.0	100.0	97.0
Large cobbles	256	100.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Small boulders	512	100.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Medium boulders	1,024	100.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Large boulders	2,048	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 11. Median particle diameter from pebble counts and sampling locations associated with each permanent cross section in the Minebank Run study reach, 2002 and 2003.

[mm, millimeters; --, not applicable; <, less than]

Cross section	Surficial pebble count (mm)	Top of left bank (mm)	Left cut bank (mm)	Subsurface main channel left (mm)	Subsurface main channel middle (mm)	Subsurface main channel right (mm)	Right cut bank (mm)	Top of right bank (mm)
Aa	20.5	0.06	0.03	6.0	16.0	0.13	--	0.20
Bb	9.0	0.008	0.014	20.0	19.0	0.31	--	0.11
Cc	50.0	0.026	0.11	31.0	70.0	70.0	10.0	0.20
Dd	36.0	0.10	--	20.0	55.0	25.0	0.20	0.05
Ee	30.0	0.09	--	0.43	6.5	8.7	--	0.19
Ff	36.0	0.12	0.10	40.0	14.0	0.27	0.04	0.05
Gg	14.0	0.60	0.60	4.0	20.0	9.5	0.35	0.35
Hh	< 2.0	--	0.19	0.82	2.5	1.0	0.15	--
Ii	10.2	0.15	0.04	9.0	4.5	0.20	--	0.20

Table 12. Grain-size distribution and computation of percent finer from composite pebble count at all permanent cross sections, Minebank Run study reach, 2003.

[mm, millimeters; %, percent; --, not applicable]

Particle description	Particle size limit (mm)	Item count	Cumulative percent finer (%)
Silt	0.062	0	0
Sand	2	219	24.2
Very fine gravel	4	8	25.1
Fine gravel	8	48	30.4
Medium gravel	16	126	44.4
Coarse gravel	32	128	58.5
Very coarse gravel	64	199	80.5
Small cobbles	128	137	95.7
Large cobbles	256	38	99.9
Small boulders	512	0	99.9
Medium boulders	1,024	0	99.9
Large boulders	2,048	1	100.0
Very large boulders	4,096	0	100.0
TOTAL	--	904	--

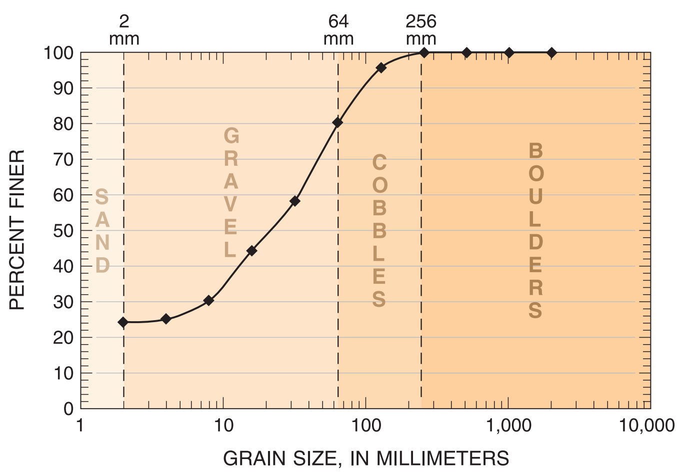

Figure 28. Composite pebble count for Minebank Run study reach above Sherwood Bridge prior to channel restoration, 2003.

Rapid aggradation and degradation of the channel bed at cross section Ee between January 2003 and July 2004 is evident (fig. 32). Large storm events on June 12–13, 2003 caused the channel bed to degrade by nearly 1 ft in this location. From June 2003 to May 2004, the net aggradation of the channel bed in this location was nearly 1.2 ft. A large storm event on May 17, 2004 caused the channel bed to degrade by over 2 ft in this location. The bed began to aggrade in the aftermath of this storm, but then degraded again during a large storm event on July 7, 2004. Analysis of the net changes in bed elevations indicate that (1) pulses of sediment are gradually transported into this section of the channel, and (2) the channel is undergoing alternating periods of storage and extreme erosion of sand and gravel at this location.

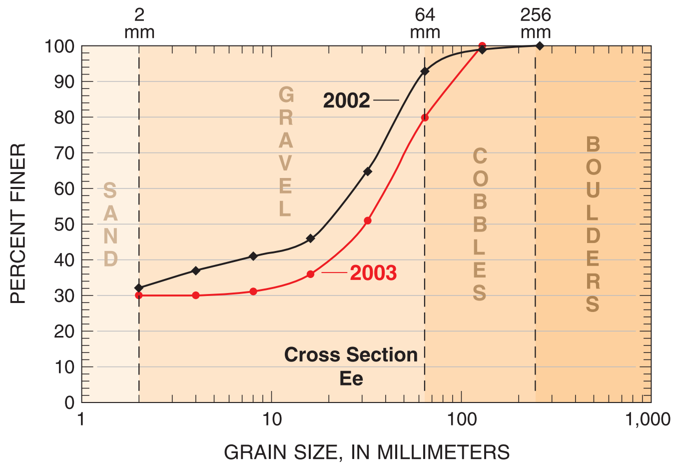

Figure 29. Comparison of particle-size distributions at cross section Ee, 2002 and 2003.

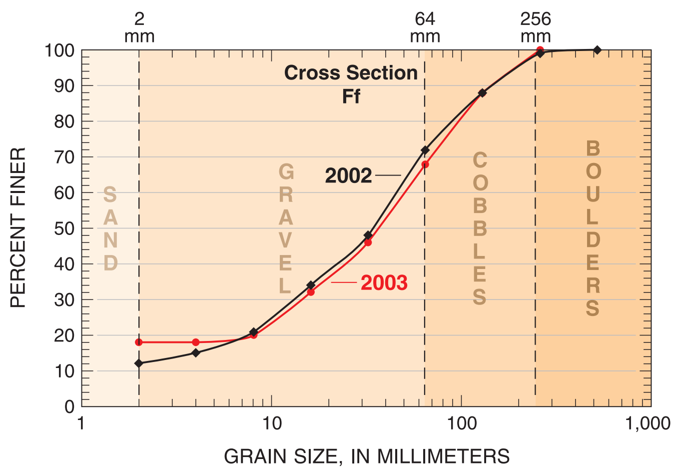

Figure 30. Comparison of particle-size distributions at cross section Ff, 2002 and 2003.

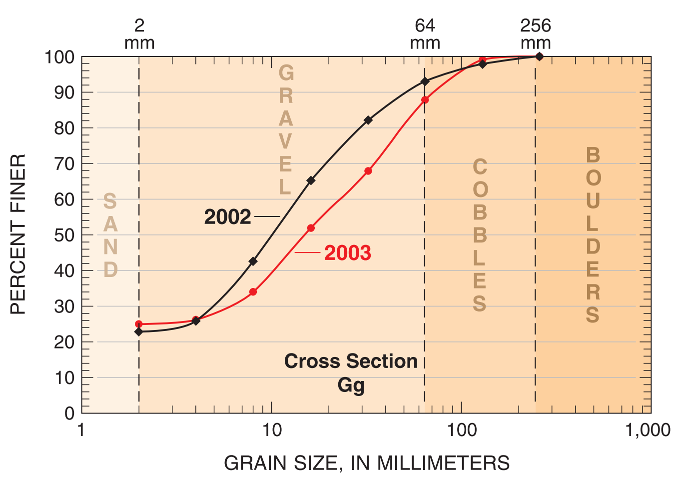

Figure 31. Comparison of particle-size distributions at cross section Gg, 2002 and 2003.

Alternating periods of aggradation and degradation of the channel bed at cross section Ff from December 2002 to July 2004 were observed (fig. 33), however, the range of net bed elevations measured during this period was approximately 0.62 ft at this location. The three storms that caused considerable degradation of the channel at cross section Ee, which is located 220 ft downstream, resulted in aggradation of the channel at cross section Ff. Overall, the channel bed showed slight aggradation during the monitoring period, with a few periods of slight degradation over time. Analysis of the net bed elevations over time indicated (1) some pulsing of sediment through the cross section, but with considerably smaller amounts of storage in this location than at cross section Ee, and (2) that channel migration could also be a contributing factor to the net aggradation observed at this location, due to considerable lateral erosion on the left bank and extension of a point bar into the channel.

Relatively small net changes in bed elevation were observed at cross section Gg during most of the period from January 2003 to July 2004. The range of net bed elevations measured during this period was approximately 0.61 ft at cross section Gg, however, the range was only about 0.20 ft from January 2003 to April 2004. The storm of May 17, 2004 caused the channel bed to degrade by 0.26 ft, and the storm of July 7, 2004 caused the channel bed to degrade by an additional 0.34 ft. Analysis of the net bed elevations over time indicated that (1) the channel cross section was relatively stable with some pulsing of sediment through the cross section, but with considerably smaller amounts of storage in this location than at either cross section Ee or Ff, and (2) the channel bed became increasingly unstable during the last 3 months of the monitoring period from May to July 2004.

Stream-Channel Classification

Rosgen (1994) developed a classification system for natural rivers that groups different types of rivers according to quantitative measurements of dimension, pattern, profile, and composition of the **bankfull** channel. Stream channels are grouped according to single- or multiple-thread channels, and then divided into stream types according to their degree of entrenchment, bankfull width/depth ratio, sinuosity, water-surface slope, and type of channel materials (Rosgen, 1994, 1996). The Rosgen system can be used to describe landforms and channel dimensions within a river valley, and is widely used as a tool for investigations of sediment supply, stream sensitivity to disturbances, recovery potential of natural channels, channel response to changes in flow regime, fish-habitat potential, and river-restoration designs (Rosgen, 1994, 1996; Anderson and others, 2002).

The stream channel in the Minebank Run study reach was classified according to Level II of the Rosgen stream-classification system, which is used to determine a morphological description of a given natural stream reach (fig. 35). Data from cross-sectional and longitudinal-profile

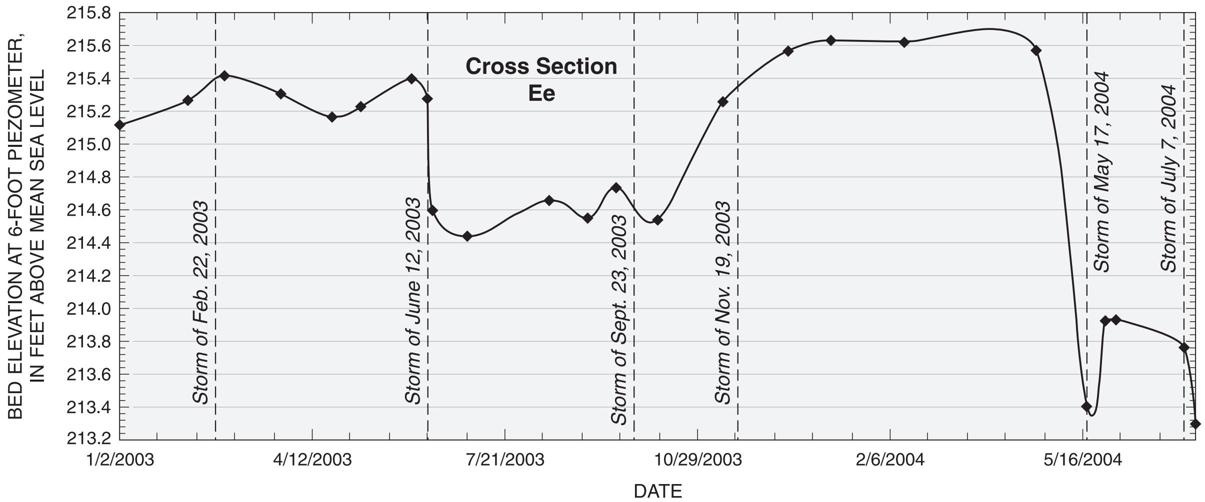

Figure 32. Net changes in bed elevation over time at cross section Ee, January 2, 2003 through July 13, 2004.

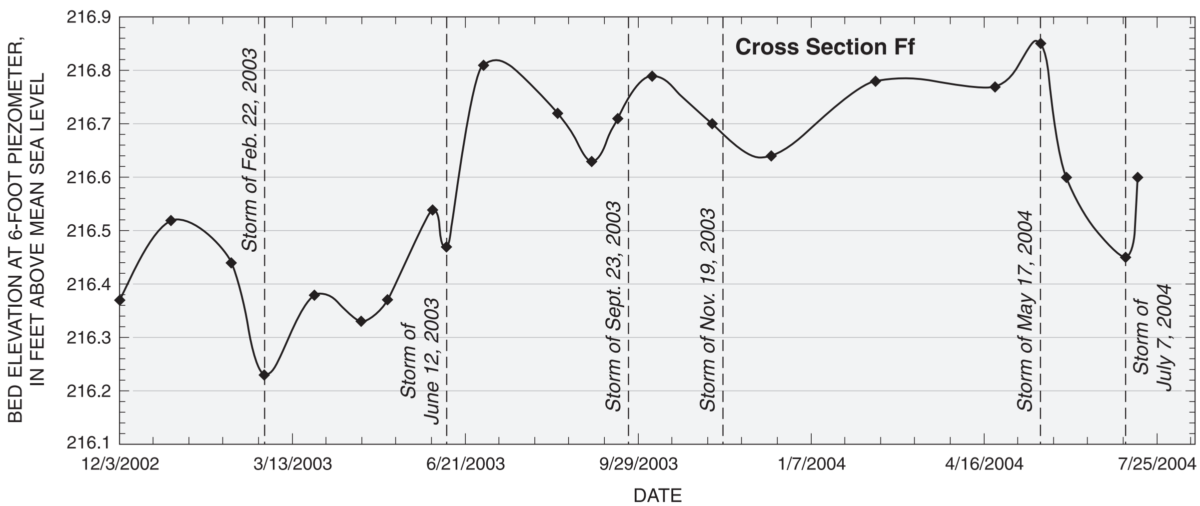

Figure 33. Net changes in bed elevation over time at cross section Ff, December 3, 2002 through July 14, 2004.

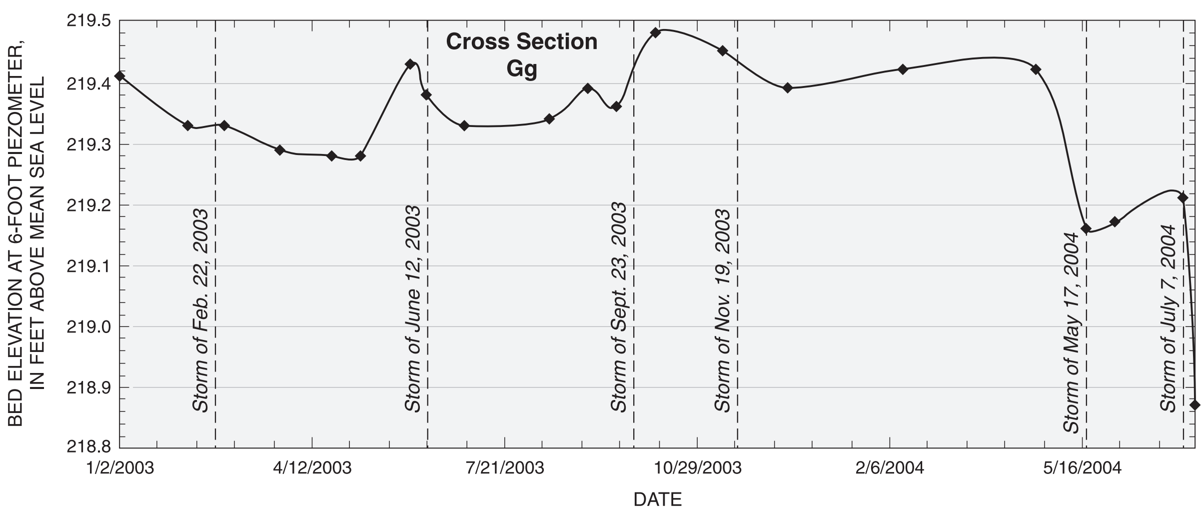

Figure 34. Net changes in bed elevation over time at cross section Gg, January 2, 2003 through July 14, 2004.

surveys collected in the study reach from 2002 to 2004 were used to determine entrenchment, width/depth ratio, and water-surface slope. Sinuosity was calculated on the basis of stream lengths that were determined from the longitudinal-profile surveys, and valley length that was measured from an aerial photo as a nearly straight-line distance between the upper and lower ends of the study reach (Baltimore County Department of Environmental Protection and Resource Management, 2000). Pebble-count data collected during 2003 were used to classify the channel materials in the study reach.

The reach containing cross section Hh was selected for classification. This reach of stream was selected because it was generally straight, and because **bankfull indicators** were clearly visible and easy to identify (Leopold, 1994; Harrelson and others, 1994). Cross section Hh is located 28 ft downstream of the continuous-record streamflow-gaging station. As a result, bankfull indicators were easily related to a gage height at the station and associated with a discharge from the stage-discharge rating that is representative of bankfull. The data variables that describe the bankfull channel at cross-section Hh during 2002 to 2004 are summarized in table 13.

On the basis of data variables shown in table 13, the Minebank Run stream channel was classified as a B stream type, indicating moderate entrenchment, a moderate width-to-depth ratio, and moderate sinuosity. Since the water-surface slope is consistently less than 2 percent in the study reach and the composite pebble count for the reach indicated a d50 of 21 mm, the stream channel was classified as a B4c channel based on the Level II Rosgen morphological descriptions (fig. 35).

The Rosgen system incorporates an entrenchment ratio variance of +/- 0.2 dimensionless units, therefore, the data in table 13 indicate that the Minebank Run stream channel could have been in transition between a B and F channel type between the 2002 and 2003 channel surveys. The entrenchment ratio then increased between the 2003 and 2004 surveys, however, indicating that the stream channel fell within the B classification at the end of the study period.

The bankfull indicators near the streamflow-gaging station and cross section Hh corresponded to the profile of point bar elevations that were surveyed during the longitudinal surveys during 2002–04. The stage-discharge rating at the streamflow-gaging station indicated a bankfull discharge of approximately 244 ft^3/s (cubic feet per second). The recurrence interval for this discharge is about a 1.0 year flood (Doheny and others, 2006). Leopold (1994) suggested that for many streams, the bankfull discharge is the flow that occurs at an average recurrence interval of approximately 1.5 years. For watersheds with large percentages of urban and suburban development, however, the bankfull discharge likely occurs more frequently and for very short durations due to the flashy nature of these streams. A flow-duration analysis using data from the streamflow-gaging station in the Minebank Run study reach indicated that the point bar elevation was exceeded by flows 0.014 percent of the time during water year 2002, 0.040 percent of the time during water year 2003, and 0.032 percent of the time during water year 2004 (Doheny and others, 2006). On average, the point bar elevation was exceeded 0.029 percent of the time during the study period. Results of the Rosgen stream classification and associated bankfull flow characteristics indicate that Minebank Run has more frequent bankfull events than typical non-urban streams on the basis of recurrence interval (Doheny and others, 2006), but the amount of time the stream stage exceeded this elevation was as little as 1.2 to 3.5 cumulative hours during a given water year due to the flashiness of the stream.

Shear-Stress Analysis

Boundary shear stress, in relation to streamflow and natural channels, is the force that flowing water imposes on the channel bed and banks of the stream. Shear stress was first described by Shields (1936) as follows:

$$T = URS \tag{1}$$

where

- T = boundary shear stress (pounds/ft^2),
- U = unit weight of water (pounds/ft^3),
- R = hydraulic radius (ft),
- S = water-surface slope (ft/ft).

Rosgen (1996) used this relation along with different stream types that were determined from various field surveys and corresponding data on mean velocity and stream discharge to develop a logarithmic relation of mean velocity versus boundary shear stress according to various stream types. Boundary shear stresses were computed for the peak discharge of 21 storms that occurred in the Minebank Run watershed from November 2001 to September 2004. Hydraulic radius was determined by use of the geometry characteristics surveyed at cross section Hh, or from channel surveys that were done for indirect measurements of peak discharge at the streamflow-gaging station. Peak water-surface slopes were computed using high-water mark elevations that were surveyed at and near the streamflow-gaging station, or from crest-stage gages that are located at the streamflow-gaging station, and approximately 180 ft downstream in the vicinity of cross section Gg and the transect of wells and piezometers farthest upstream in the study reach. Corresponding mean velocities were computed for each storm event using the peak discharge for the storm and the corresponding cross-sectional area at cross section Hh. The results are summarized in table 14.

The computed boundary shear stress values were plotted against the peak discharge for each storm (fig. 36) and against corresponding mean velocity (fig. 37). Simple linear regression was used to determine logarithmic relations for both boundary shear stress versus peak discharge and boundary shear stress versus mean velocity. The following equations

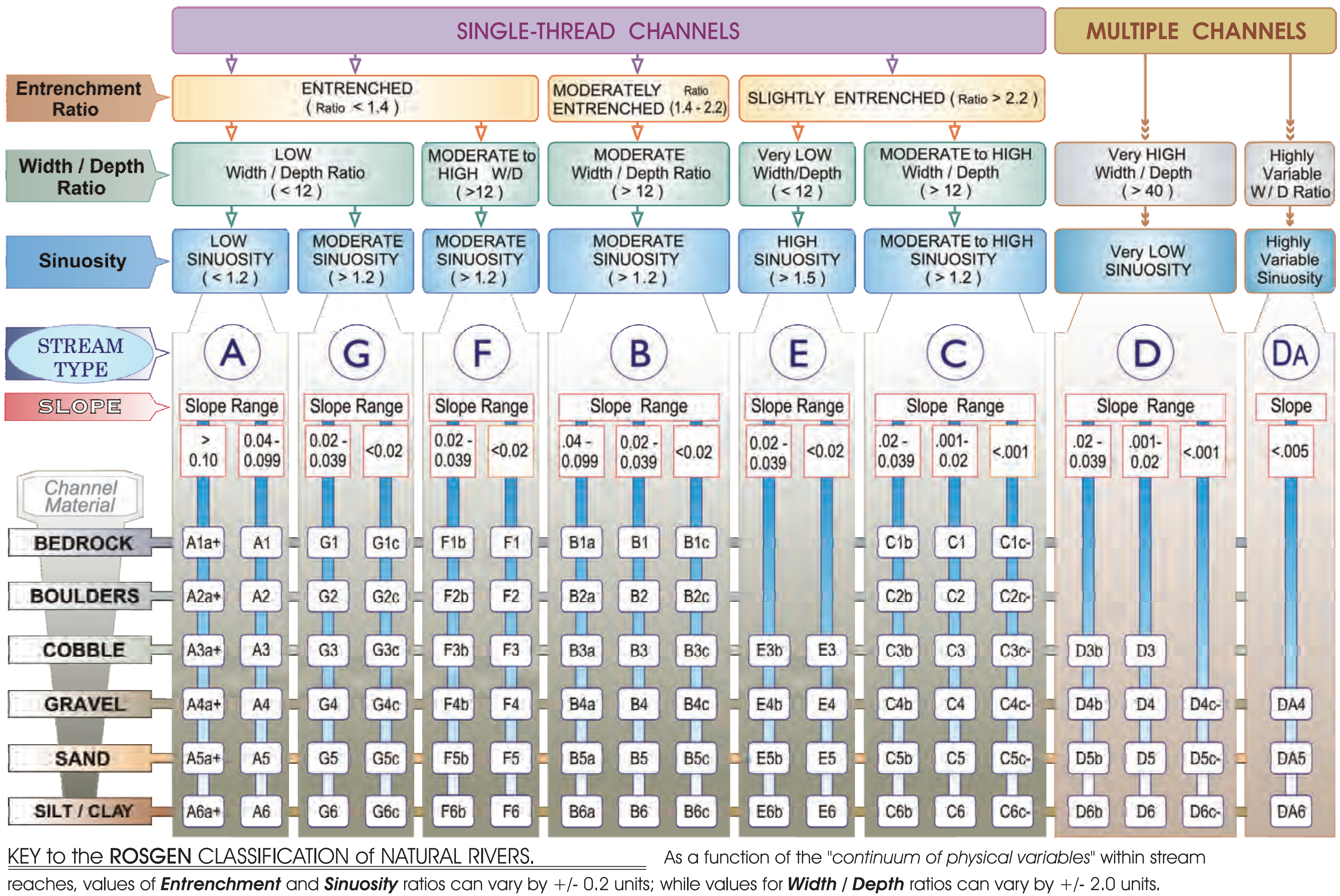

Figure 35. Key for the Rosgen classification of natural rivers (modified from Rosgen, 1996).

Table 13. Data variables describing the bankfull channel at cross section Hh that were used for Rosgen classification of the stream channel, 2002–04.

[ft, feet; ft^2, square feet]

Data variable	2002	2003	2004
Bankfull elevation (ft above mean sea level)	222.58	222.56	222.74
Cross-sectional area (ft^2)	50.6	62.9	66.3
Wetted perimeter (ft)	31.9	42.0	37.6
Hydraulic radius (ft)	1.58	1.51	1.76
Mean depth (ft)	1.68	1.60	1.87
Maximum depth (ft)	2.80	3.12	2.99
Top width (ft)	30.0	39.7	35.5
Entrenchment width (in ft, at twice maximum bankfull depth)	50.9	53.4	54.0
Entrenchment ratio (ft/ft)	1.70	1.35	1.52
Width/depth ratio (ft/ft)	17.9	24.8	19.0
Sinuosity (ft/ft)	1.16	1.16	1.16
Water-surface slope (ft/ft)	0.0100	0.0092	0.0095

were developed based on the data from the Minebank Run study reach:

$$Q = 385(SS)^{1.418} \tag{2}$$

where

Q = peak discharge in ft^3/s,

and

SS = boundary shear stress in lb/ft^2.

$$V = 4.715(SS)^{0.533} \tag{3}$$

where

V = mean velocity at the peak discharge in ft/s,

and

SS = boundary shear stress in lb/ft^2.

The equation for boundary shear stress versus peak discharge indicated a **coefficient of determination** (R^2) of 0.84. The **residual standard error** (RSE) was 0.127 log units, or approximately 33 percent. The equation for boundary shear stress versus mean velocity indicated an R^2 of 0.83. The RSE was 0.051 log units, or approximately 31.8 percent.

The relation for boundary shear stress versus mean velocity was also plotted on the relation developed by Rosgen (1996) for boundary shear stress versus mean velocity by stream type (fig. 38). Most boundary shear stress and mean velocity values for Minebank Run are larger than non-urban B channel types that were classified and plotted by Rosgen (1996). The slope of the regression line for Minebank Run is considerably flatter than the relations developed by Rosgen (fig. 38). This indicates that for Minebank Run, small changes in mean velocity result in larger changes in boundary shear

Table 14. Data variables and boundary shear stress computations for 21 storm runoff events in the Minebank Run study reach, November 2001 through September 2004.

[ft^3/s, cubic feet per second; ft^2, square feet; ft/s, feet per second; ft, feet; lb/ft^2, pound per square foot]

Date of storm event	Peak discharge (ft^3/s)	Cross-sectional area (ft^2)	Mean velocity (ft/s)	Hydraulic radius (ft)	Water-surface slope (ft/ft)	Boundary shear stress (lb/ft^2)
11/25/2001	367	76.7	4.78	1.92	0.0097	1.16
3/3/2002	95	30.3	3.14	1.05	0.0091	0.60
3/26/2002	133	38.0	3.50	1.15	0.0093	0.67
4/19/2002	401	81.7	4.91	2.00	0.0098	1.22
5/2/2002	247	61.3	4.03	1.59	0.0077	0.76
6/6/2002	466	88.3	5.28	2.12	0.0103	1.36
8/3/2002	725	114	6.34	2.38	0.0080	1.19
2/22/2003	253	59.6	4.24	1.42	0.0063	0.56
6/12/2003	1,390	150	9.29	2.97	0.0112	2.08
9/23/2003	834	141	5.91	2.74	0.0095	1.62
10/14/2003	411	99.4	4.13	2.19	0.0081	1.11
10/27/2003	234	60.6	3.86	1.75	0.0063	0.69
11/19/2003	700	126	5.54	2.49	0.0101	1.57
12/11/2003	194	53.3	3.64	1.62	0.0055	0.56
5/17/2004	720	130	5.56	2.54	0.0091	1.44
5/25/2004	266	71.4	3.73	1.64	0.0054	0.55
6/25/2004	295	78.8	3.74	1.79	0.0062	0.69
7/7/2004	945	148	6.37	2.84	0.0103	1.82
7/27/2004	919	146	6.30	2.80	0.0109	1.90
9/18/2004	190	51.2	3.71	1.58	0.0067	0.66
9/28/2004	211	56.5	3.73	1.68	0.0058	0.61

stress when compared to the non-urban stream channels plotted by Rosgen (1996). Rapid increases in boundary shear stress indicate rapidly increasing forces that the flowing water imposes on the channel bed and banks of the stream channel, and thus a greater ability for the stream to transport sediment.

Data Limitations

The geomorphic data collected during this study are representative of approximately 1–1.5 years in the long-term geomorphic evolution of the stream channel. Data collection over longer periods could provide a longer term perspective on the geomorphic form and processes of the stream channel.

Longitudinal profiles and cross-sectional data were collected by use of conventional leveling techniques. Although permanent monuments were used to identify and re-survey cross sections, there is a degree of difficulty in maintaining the same stations from survey to survey, and conventional leveling includes a small degree of human error in interpreting readings from the survey rod. Due to geomorphic changes in the stream channel over time, there is also a small degree of error in maintaining exact longitudinal stationing from survey to survey.

Pebble count data represent a random sampling of particle sizes from the channel bed. As a result, small differences in particle-size distribution may, in some cases, be explained by random variability of the samples taken from the channel bed.

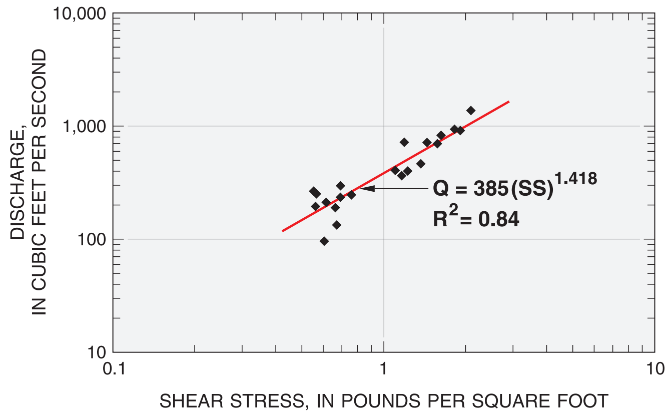

Figure 36. Boundary shear stress versus peak discharge in the Minebank Run study reach, November 2001 through September 2004.

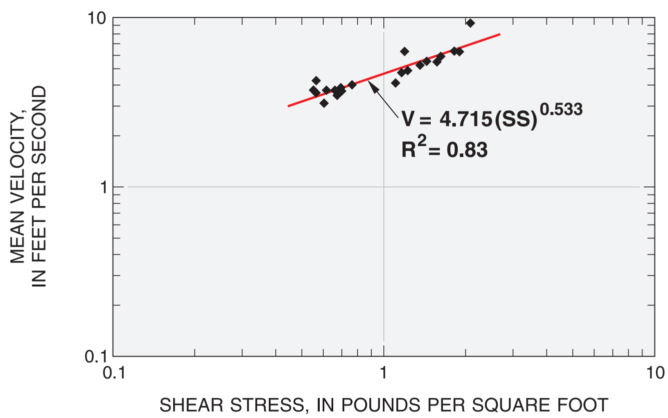

Figure 37. Boundary shear stress versus mean velocity at the peak discharge during storm events in the Minebank Run study reach, November 2001 through September 2004.

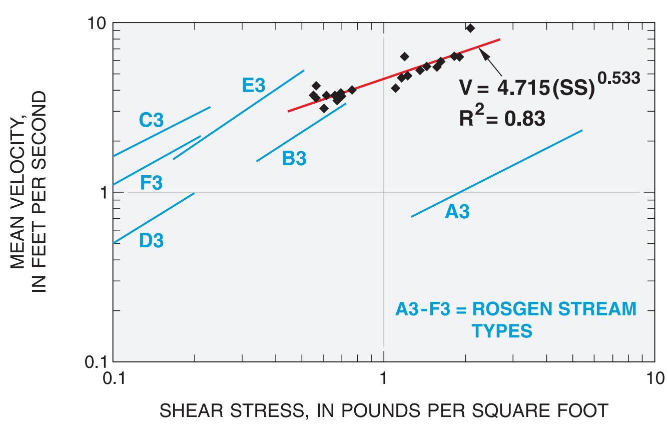

Figure 38. Boundary shear stress versus mean velocity at the peak discharge during storm events in the Minebank Run study reach, November 2001 through September 2004, and relations developed by Rosgen stream type for non-urban stream channels (modified from Rosgen, 1996).

Summary and Conclusions

This report describes the methods used to collect pre-restoration geomorphic data in a selected study reach of Minebank Run near Towson, Maryland. Data collected from 2002 to 2004 include continuous-record streamflow; surveyed elevations of the channel bed, water surface, and bank features; surveyed cross sections; measurements of bank erosion and maximum scour by use of bank pins and scour chains; pebble counts and samples of the channel bed and banks for determination of grain-size analyses; measurements of bed elevations over time in selected locations; and high-water mark elevations from storm runoff events in the watershed.

These data were used to assess pre-restoration geomorphic characteristics and pre-restoration geomorphic changes over time in the Minebank Run study reach. Longitudinal profiles of the channel bed, water surface, and bank features were developed from field surveys. Changes in cross-section geometry were documented. Grain-size distributions of the channel bed and banks were developed from pebble counts and laboratory sediment analysis. Net changes in the elevation of the channel bed over time were documented at selected locations. The stream channel was classified according to morphological descriptions using measurements of slope, entrenchment ratio, width-to-depth ratio, sinuosity, and median particle diameter of the channel materials. Boundary shear stress was analyzed in the vicinity of the streamflow-gaging station by use of hydraulic variables that were computed from the cross-section surveys, and slope measurements that were made by use of crest-stage gages in the study reach.

Comparison of the longitudinal profiles showed considerable changes in the percentage and distribution of riffles, pools, and runs in the study reach between 2002 and 2004. In spite of major geomorphic changes to sections of the channel profile from storm events, the overall slope of the channel bed and other features remained constant at about 1 percent.

The cross-sectional surveys indicated net increases in cross-sectional area, mean depth, and channel width over time at several locations, which indicate channel degradation and widening. Large amounts of sediment were being stored in the study reach at two locations. Data from the scour chains indicated maximum scour of 1.4 feet, and several cross sections where maximum scour exceeded 1.0 feet during storm events. Lateral migration of the banks varied widely throughout the study reach and ranged from 0.2 feet to as much as 7.9 feet. Changes in net bed elevation measured at selected locations indicated a maximum aggradation of nearly 1.2 feet in one location over time, degradation of the channel bed of nearly 2 feet in one location during a storm event in May 2004, and pulses of sediment that were transported through the study reach over time.

Particle-size analyses of the channel bed from pebble counts indicated a median particle diameter of 20.5 millimeters for the study reach with over 24 percent of the total count consisting of sand particles. Laboratory analyses of bank samples indicated that the material in the channel banks was predominantly silt/clay, or a mixture of silt/clay and very fine to coarse sand.

The Minebank Run stream channel was classified as a B4c channel on the basis of morphological descriptions in the Rosgen Stream Classification System. The B4c classification describes a single-thread stream channel with a moderate entrenchment ratio of 1.4 to 2.2; a width-to-depth ratio greater than 12; moderate sinuosity of 1.2 or greater; a water-surface slope of less than 2 percent; and a median particle diameter in the gravel range (2–64 millimeters).

The analysis of boundary shear stress showed larger mean velocities and boundary shear stress values for Minebank Run when compared to the relation for non-urban B channel types plotted by Rosgen. The slope of the regression line for mean velocity versus boundary shear stress at Minebank Run was noticeably smaller than the relations developed by Rosgen for non-urban channel types. This indicates that relatively small increases in mean velocity can result in large increases in boundary shear stress in stream channels with highly developed watersheds, such as Minebank Run.

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Glossary

A

Alluvium Sedimentary material that was deposited by flowing water. Examples of alluvial deposits include deltas, point bars, and sand in the flood-plain areas of rivers or streams.

B

Bankfull (stage or discharge) Bankfull stage refers to the water-surface elevation at the level of the active flood plain in a stream channel. Bankfull discharge refers to the stream discharge at the level of the active flood plain. It is also the discharge that, over time, transports the largest volumes of sediment, and forms and maintains the morphological features in the stream channel.

Bankfull indicator(s) Geomorphic features in a stream channel that define the elevation of the active flood plain. These features might include the top of point bar surfaces and depositional features, breaks or changes in bank vegetation, changes or breaks in bank slope, changes in channel-material sizes or distribution on the channel banks, the upper extent of bank undercuts, and stain lines on rocks.

Boundary shear stress The force, in pounds per square foot, that flowing water applies to the channel bed and banks of a stream.

C

Coefficient of determination (R^2) The fraction of the variation in the dependent variable that is explained by the explanatory variable(s). R^2 ranges between 0 and 1. The closer R^2 is to 1, the better the explanation of variation in the dependent variable with changes in the explanatory variable(s).

Colluvium Loose deposits of collapsed rock debris that accumulate at the base of a cliff or sloping valley.

Continuous-record streamflow-gaging station Location where a water-stage recorder is used to collect continuous time-series stage data that are related to systematic discharge measurements at the station. Continuous-record streamflow-gaging stations are often operated for the purpose of long-term monitoring or as part of hydrologic investigations.

Crest-stage gage A device that will register the peak stage of the stream occurring between inspections of the gage. Crest-stage gages are typically used as a supplement to a water-stage recorder since the peak stage of a storm can occur in between recorded stage values. Crest-stage gages can be used to obtain high-water marks at a given location during a flood, or to determine water-surface slopes at different stream stages if placed in multiple locations along a reach of stream. A stage-discharge relation for the location of a crest-stage gage can be developed using discharge data obtained by indirect measurements of peak flow, or direct measurement of a range of discharges by use of a current meter.

D

Daily mean discharge Discharge that is computed as the arithmetic mean of the instantaneous discharge values for a given day of the water year.

F

Fall Line The line marking the point on each stream where the flow descends from the eastern section of the Piedmont Physiographic Province to the western section of the Coastal Plain Physiographic Province in Maryland. The Fall Line is characterized by an abrupt decrease in channel slope in transition between the Piedmont and the Coastal Plain Physiographic Provinces.

Flashy A stream or watershed that tends to produce narrow, steeply peaked storm hydrographs that rise and fall very quickly.

H

Hydraulic radius The cross-sectional area of a channel divided by the wetted perimeter.

L

Lateral erosion Erosion in which the removal of bank material extends laterally from the toe of the bank.

P

Percent finer A cumulative percentage, associated with a particular particle size or diameter, that represents how much of the material that composes the channel bed or banks is smaller, or finer, than that particle diameter.

Piezometer An open-ended vertical pipe that is used for measurement of pressure and changes in pressure at a selected depth within an aquifer.

R

Relief The variation between the highest and lowest elevations at any location in a watershed, using a common elevation datum.

Residual standard error (RSE) The square root of the mean square error, which is the sum of the squared differences between the observed and predicted values divided by the number of observations minus 2. Residual standard error is also commonly known as the standard error of estimate.

Run A longitudinal section of stream channel that has a moderate current, moderate depth, and a relatively smooth water surface.

S

Sinuosity The ratio of stream length to valley length. The minimum value for sinuosity is 1.0 for a straight channel, and increases depending on the level of meandering in the reach of interest.

Stability The ability of a stream or river to transport its flow and sediment while maintaining its dimension, pattern, and profile with no net change in aggradation or degradation.

Stage-discharge rating A logarithmic curve of stream stage versus stream discharge that is developed from a series of discharge measurements made in a particular location. A stage-discharge rating can also be presented as a table that is prepared from the curve.

T

Terrace An abandoned flood plain in a river or stream. A flood plain may become abandoned when a stream channel degrades and forms new channel features that are indicative of the active flood plain.

Thalweg The lowest elevation along a cross section in a stream channel.

Top of topographic bank The topographic break in elevation that separates the stream valley from the over-bank area.

W

Water year The 12-month period beginning October 1 and ending September 30. The water year is designated by the calendar year in which it ends and includes 9 of the 12 months. For example, the year beginning October 1, 2003 and ending September 30, 2004, is called “water year 2004.”

Wetted perimeter The length along the cross-sectional boundary of a channel that is contacted by water. In an open channel, such as a stream or river, the cross-sectional boundary is the channel bed and banks.

Appendix 1

Appendix 1. Changes in cross-section geometry at permanent cross section Aa, Minebank Run study reach, 2002 through 2004.

[ft, feet; ft², square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft²) 2002	Cross-sectional area (ft²) 2003	Cross-sectional area (ft²) 2004	Wetted perimeter (ft) 2002	Wetted perimeter (ft) 2003	Wetted perimeter (ft) 2004	Hyd. radius (ft) 2002	Hyd. radius (ft) 2003	Hyd. radius (ft) 2004	Channel width (ft) 2002	Channel width (ft) 2003	Channel width (ft) 2004	Mean channel depth (ft) 2002	Mean channel depth (ft) 2003	Mean channel depth (ft) 2004
212.00	48.4	47.1 (-2.7%)	57.9 (+19.6%)	31.5	32.6	35.9	1.54	1.44	1.61	29.5	30.4	32.5	1.65	1.55	1.78
212.50	63.4	62.5 (-1.4%)	74.4 (+17.4%)	33.5	34.1	37.4	1.89	1.84	1.99	30.7	31.3	33.3	2.06	2.00	2.23
213.00	79.1	78.4 (-0.9%)	91.3 (+15.4%)	35.5	35.5	39.5	2.23	2.21	2.31	32.2	32.2	34.9	2.46	2.44	2.62
213.50	95.6	95.1 (-0.5%)	109.2 (+14.2%)	37.6	38.5	41.9	2.54	2.47	2.61	33.7	34.8	36.8	2.83	2.73	2.97
214.00	112.9	113.2 (+0.3%)	128.0 (+13.4%)	39.7	41.8	44.3	2.84	2.71	2.89	35.3	37.6	38.7	3.20	3.01	3.31
214.50	165.2	165.9 (+0.4%)	184.1 (+11.4%)	78.0	81.7	82.3	2.12	2.03	2.24	72.6	76.4	75.7	2.28	2.17	2.43
215.00	201.7	204.2 (+1.2%)	222.2 (+10.2%)	79.7	82.9	84.0	2.53	2.46	2.65	73.7	77.0	76.9	2.74	2.65	2.89
215.50	238.9	242.9 (+1.7%)	261.0 (+9.3%)	81.4	84.1	85.8	2.93	2.89	3.04	74.9	77.7	78.1	3.19	3.13	3.34
216.00	276.6	282.0 (+2.0%)	300.3 (+8.6%)	83.7	86.3	87.8	3.30	3.27	3.42	76.7	79.3	79.6	3.61	3.56	3.77
216.15	288.2	293.9 (+2.0%)	312.4 (+8.4%)	85.3	87.1	90.1	3.38	3.38	3.47	78.2	80.0	81.9	3.68	3.68	3.82

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Bb, Minebank Run study reach, 2002 through 2004.—Continued

[ft, feet; ft^2, square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft^2) 2002	Cross-sectional area (ft^2) 2003	Cross-sectional area (ft^2) 2004	Wetted perimeter (ft) 2002	Wetted perimeter (ft) 2003	Wetted perimeter (ft) 2004	Hyd. radius (ft) 2002	Hyd. radius (ft) 2003	Hyd. radius (ft) 2004	Channel width (ft) 2002	Channel width (ft) 2003	Channel width (ft) 2004	Mean channel depth (ft) 2002	Mean channel depth (ft) 2003	Mean channel depth (ft) 2004
212.17	50.1	33.4 (-33.3%)	32.0 (-36.1%)	33.9	28.1	28.8	1.48	1.19	1.11	32.2	27.3	28.0	1.56	1.22	1.14
212.50	62.2	44.5 (-28.5%)	42.8 (-31.2%)	41.7	38.4	38.6	1.49	1.16	1.11	39.7	37.6	37.7	1.57	1.18	1.13
213.00	82.7	64.2 (-22.4%)	62.3 (-24.7%)	44.6	42.0	41.7	1.85	1.53	1.49	42.2	41.0	40.4	1.96	1.57	1.54
213.50	104.2	85.8 (-17.7%)	83.3 (-20.1%)	46.7	46.6	44.9	2.23	1.84	1.86	43.8	45.4	43.2	2.38	1.89	1.93
214.00	126.5	108.5 (-14.2%)	105.5 (-16.6%)	48.9	48.7	47.5	2.59	2.24	2.22	45.5	47.0	45.7	2.78	2.32	2.31
214.50	149.9	132.9 (-11.3%)	129.0 (-13.9%)	52.0	51.1	50.5	2.89	2.60	2.56	48.2	48.9	48.4	3.11	2.72	2.66
215.00	178.2	160.6 (-9.9%)	156.6 (-12.1%)	66.5	61.7	64.1	2.68	2.60	2.44	62.3	59.0	61.5	2.86	2.72	2.55
215.50	210.4	191.5 (-9.0%)	188.7 (-10.3%)	70.4	67.6	70.2	2.99	2.83	2.69	65.8	64.4	67.1	3.20	2.97	2.81
216.00	243.9	224.0 (-8.2%)	222.9 (-8.6%)	74.0	69.5	73.6	3.30	3.22	3.03	68.9	65.8	70.0	3.54	3.41	3.18
216.50	280.0	259.2 (-7.4%)	259.2 (-7.4%)	82.8	80.0	81.6	3.38	3.24	3.17	77.3	75.8	77.6	3.62	3.42	3.34
216.54	283.1	262.2 (-7.4%)	262.3 (-7.3%)	83.6	81.3	82.3	3.39	3.22	3.19	78.1	77.1	78.2	3.63	3.40	3.36

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Cc, Minebank Run study reach, 2002 through 2004.

[ft, feet; ft^2, square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft^2)	Cross-sectional area (ft^2)	Cross-sectional area (ft^2)	Wetted perimeter (ft)	Wetted perimeter (ft)	Wetted perimeter (ft)	Hyd. radius (ft)	Hyd. radius (ft)	Hyd. radius (ft)	Channel width (ft)	Channel width (ft)	Channel width (ft)	Mean channel depth (ft)	Mean channel depth (ft)	Mean channel depth (ft)
	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
214.05	40.0	50.5 (+26.3%)	46.4 (+16.0%)	45.3	46.6	46.9	0.88	1.08	0.99	43.7	44.5	43.8	0.92	1.14	1.06
214.50	59.9	70.7 (+18.0%)	66.4 (+10.9%)	46.7	47.8	48.6	1.28	1.48	1.37	44.8	45.3	45.2	1.34	1.56	1.47
215.00	82.5	93.5 (+13.3%)	89.4 (+8.4%)	48.0	49.1	50.5	1.72	1.91	1.77	45.5	46.1	46.9	1.81	2.03	1.91
215.50	105.4	116.7 (+10.7%)	113.3 (+7.5%)	49.1	50.2	52.7	2.15	2.32	2.15	46.0	46.6	48.7	2.29	2.51	2.33
215.95	126.1	137.8 (+9.3%)	150.7 (+19.5%)	50.1	51.6	86.0	2.52	2.67	1.75	46.5	47.5	81.6	2.72	2.90	1.85
216.50	188.8	200.1 (+6.0%)	196.4 (+4.0%)	88.1	90.8	89.9	2.14	2.20	2.18	83.8	85.9	85.1	2.25	2.33	2.31
217.00	231.5	243.3 (+5.1%)	239.8 (+3.6%)	92.9	92.5	93.8	2.49	2.63	2.56	88.3	87.1	88.7	2.62	2.79	2.70
217.50	276.7	287.6 (+3.9%)	285.0 (+3.0%)	98.2	95.9	97.3	2.82	3.00	2.93	93.3	90.1	92.0	2.97	3.19	3.10
218.00	324.8	335.0 (+3.1%)	332.0 (+2.2%)	106.3	107.0	103.7	3.06	3.13	3.20	101.2	101.1	98.3	3.21	3.31	3.38
218.18	343.4	353.8 (+3.0%)	350.3 (+2.0%)	111.0	114.7	110.2	3.09	3.09	3.18	106.0	108.8	104.8	3.24	3.25	3.34

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Dd, Minebank Run study reach, 2002 through 2004.—Continued

[ft, feet; ft², square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft²) 2002	Cross-sectional area (ft²) 2003	Cross-sectional area (ft²) 2004	Wetted perimeter (ft) 2002	Wetted perimeter (ft) 2003	Wetted perimeter (ft) 2004	Hyd. radius (ft) 2002	Hyd. radius (ft) 2003	Hyd. radius (ft) 2004	Channel width (ft) 2002	Channel width (ft) 2003	Channel width (ft) 2004	Mean channel depth (ft) 2002	Mean channel depth (ft) 2003	Mean channel depth (ft) 2004
215.00	23.6	30.0 (+27.1%)	31.2 (+32.2%)	23.9	26.5	30.9	0.99	1.13	1.01	23.1	25.0	29.4	1.02	1.20	1.06
215.50	35.4	42.7 (+20.6%)	46.1 (+30.2%)	25.7	27.9	32.3	1.38	1.53	1.43	24.5	26.0	30.2	1.45	1.64	1.53
216.00	49.4	56.1 (+13.6%)	61.4 (+24.3%)	32.7	30.0	33.8	1.51	1.87	1.82	31.1	27.8	31.1	1.59	2.02	1.97
216.50	65.4	72.3 (+10.6%)	78.3 (+19.7%)	35.2	36.7	39.6	1.86	1.97	1.98	33.2	34.1	36.5	1.97	2.12	2.14
217.00	83.3	90.7 (+8.9%)	97.9 (+17.5%)	40.0	42.0	44.8	2.08	2.16	2.18	37.7	38.9	41.4	2.21	2.33	2.36
217.50	104.5	111.9 (+7.1%)	119.9 (+14.7%)	48.6	48.8	51.6	2.15	2.29	2.32	45.9	45.4	47.8	2.27	2.46	2.51
218.00	128.5	136.1 (+5.9%)	145.8 (+13.5%)	55.4	58.5	61.9	2.32	2.33	2.36	52.4	54.7	57.7	2.45	2.49	2.53
218.38	182.7	190.1 (+4.1%)	200.0 (+9.5%)	94.6	96.5	98.0	1.93	1.97	2.04	90.8	91.8	92.7	2.01	2.07	2.16

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Ee, Minebank Run study reach, 2002 through 2004.—Continued

[ft, feet; ft^2, square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft^2) 2002	Cross-sectional area (ft^2) 2003	Cross-sectional area (ft^2) 2004	Wetted perimeter (ft) 2002	Wetted perimeter (ft) 2003	Wetted perimeter (ft) 2004	Hyd. radius (ft) 2002	Hyd. radius (ft) 2003	Hyd. radius (ft) 2004	Channel width (ft) 2002	Channel width (ft) 2003	Channel width (ft) 2004	Mean channel depth (ft) 2002	Mean channel depth (ft) 2003	Mean channel depth (ft) 2004
216.00	21.1	29.6 (+40.3%)	23.5 (+11.4%)	21.5	28.0	29.5	0.98	1.06	0.80	20.9	27.3	28.4	1.01	1.08	0.83
216.50	32.1	44.0 (+37.1%)	38.0 (+18.4%)	24.9	30.7	31.1	1.29	1.43	1.22	24.1	29.9	29.5	1.33	1.47	1.29
217.00	56.6	62.1 (+9.7%)	53.1 (-6.2%)	42.4	45.0	33.1	1.33	1.38	1.61	41.3	43.9	31.2	1.37	1.42	1.70
217.50	78.6	85.1 (+8.3%)	72.3 (-8.0%)	47.7	51.4	50.5	1.65	1.66	1.43	46.2	50.0	48.3	1.70	1.70	1.50
218.00	102.2	110.5 (+8.1%)	97.4 (-4.7%)	49.6	53.2	53.8	2.06	2.08	1.81	47.8	51.4	51.4	2.14	2.15	1.90
218.50	127.6	136.6 (+7.1%)	123.6 (-3.1%)	54.1	55.2	56.2	2.36	2.47	2.20	52.0	53.2	53.6	2.45	2.57	2.31
219.00	154.1	163.7 (+6.2%)	150.8 (-2.1%)	57.5	57.3	58.3	2.68	2.86	2.59	55.2	55.0	55.4	2.79	2.97	2.72
219.38	175.9	184.8 (+5.1%)	172.1 (-2.2%)	62.0	58.6	59.8	2.84	3.15	2.88	59.4	56.1	56.7	2.96	3.29	3.04

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Ff, Minebank Run study reach, 2002 through 2004.—Continued

[ft, feet; ft^2, square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft^2) 2002	Cross-sectional area (ft^2) 2003	Cross-sectional area (ft^2) 2004	Wetted perimeter (ft) 2002	Wetted perimeter (ft) 2003	Wetted perimeter (ft) 2004	Hyd. radius (ft) 2002	Hyd. radius (ft) 2003	Hyd. radius (ft) 2004	Channel width (ft) 2002	Channel width (ft) 2003	Channel width (ft) 2004	Mean channel depth (ft) 2002	Mean channel depth (ft) 2003	Mean channel depth (ft) 2004
219.00	30.6	39.1 (+27.8%)	41.8 (+36.6%)	25.4	26.1	26.0	1.20	1.50	1.60	23.6	25.0	24.5	1.29	1.56	1.70
219.50	44.4	53.6 (+20.7%)	54.6 (+23.0%)	34.7	34.2	28.6	1.28	1.57	1.91	32.6	32.8	26.7	1.36	1.63	2.04
220.00	62.0	72.0 (+16.1%)	71.9 (+16.0%)	39.6	40.9	41.0	1.57	1.76	1.76	37.3	39.1	38.7	1.66	1.84	1.86
220.50	81.2	92.2 (+13.5%)	92.1 (+13.4%)	42.0	43.7	44.5	1.93	2.11	2.07	39.3	41.5	42.1	2.07	2.22	2.19
221.00	101.3	113.5 (+12.0%)	113.9 (+12.4%)	44.7	46.8	47.8	2.27	2.42	2.38	41.6	44.2	45.1	2.43	2.57	2.53
221.50	123.5	136.9 (+10.9%)	137.3 (+11.2%)	54.3	56.2	53.7	2.27	2.43	2.56	50.9	53.2	50.7	2.43	2.57	2.71
222.00	312.8	323.6 (+3.5%)	324.0 (+3.6%)	137.2	141.8	142.8	2.28	2.28	2.27	132.5	137.6	138.7	2.36	2.35	2.34
222.34	358.1	370.6 (+3.5%)	371.4 (+3.7%)	138.6	143.7	147.0	2.58	2.58	2.53	133.7	139.3	142.6	2.68	2.66	2.60

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Gg, Minebank Run study reach, 2002 through 2004.—Continued

[ft, feet; ft², square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft²)	Cross-sectional area (ft²)	Cross-sectional area (ft²)	Wetted perimeter (ft)	Wetted perimeter (ft)	Wetted perimeter (ft)	Hyd. radius (ft)	Hyd. radius (ft)	Hyd. radius (ft)	Channel width (ft)	Channel width (ft)	Channel width (ft)	Mean channel depth (ft)	Mean channel depth (ft)	Mean channel depth (ft)
	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004	2002	2003	2004
220.80	39.1	41.9 (+7.2%)	42.8 (+9.5%)	34.8	36.8	37.9	1.12	1.14	1.13	33.4	36.0	37.1	1.17	1.17	1.15
221.00	45.8	49.2 (+7.4%)	50.4 (+10.0%)	35.4	37.9	39.2	1.29	1.30	1.29	33.8	37.0	38.2	1.36	1.33	1.32
221.50	62.9	68.2 (+8.4%)	69.7 (+10.8%)	36.7	40.1	40.7	1.71	1.70	1.72	34.7	38.9	39.3	1.81	1.75	1.78
222.00	80.8	88.1 (+9.0%)	89.6 (+10.9%)	39.8	42.0	42.1	2.03	2.10	2.13	37.5	40.5	40.3	2.15	2.18	2.22
222.50	100.6	108.8 (+8.2%)	110.2 (+9.5%)	44.0	44.9	44.6	2.29	2.43	2.47	41.6	43.1	42.4	2.42	2.52	2.60
223.00	122.3	133.3 (+9.0%)	132.1 (+8.0%)	48.2	56.4	47.5	2.54	2.36	2.78	45.7	54.6	44.9	2.68	2.44	2.94
223.48	149.7	160.6 (+7.3%)	162.2 (+8.4%)	62.0	61.3	66.5	2.41	2.62	2.44	59.2	59.3	63.7	2.53	2.71	2.55

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

Appendix 1. Changes in cross-section geometry at permanent cross section Ii, Minebank Run study reach, 2002 through 2004.—Continued

[ft, feet; ft², square feet; Hyd., Hydraulic; %, percent]

Elevation (ft above mean sea level)	Cross-sectional area (ft²) 2002	Cross-sectional area (ft²) 2003	Cross-sectional area (ft²) 2004	Wetted perimeter (ft) 2002	Wetted perimeter (ft) 2003	Wetted perimeter (ft) 2004	Hyd. radius (ft) 2002	Hyd. radius (ft) 2003	Hyd. radius (ft) 2004	Channel width (ft) 2002	Channel width (ft) 2003	Channel width (ft) 2004	Mean channel depth (ft) 2002	Mean channel depth (ft) 2003	Mean channel depth (ft) 2004
224.00	39.8	45.5 (+14.3%)	60.1 (+51.0%)	37.9	34.4	45.2	1.05	1.32	1.33	35.8	32.7	43.3	1.11	1.39	1.39
224.50	58.6	66.3 (+13.1%)	82.2 (+40.3%)	43.2	46.5	47.4	1.36	1.43	1.73	40.3	44.2	45.1	1.45	1.50	1.82
225.00	82.1	90.6 (+10.4%)	106.9 (+30.2%)	51.2	52.7	54.4	1.60	1.72	1.97	47.6	49.9	51.6	1.73	1.82	2.07
225.50	108.5	117.1 (+7.9%)	134.1 (+23.6%)	61.6	61.1	63.6	1.76	1.92	2.11	57.6	57.9	60.3	1.88	2.03	2.22
226.00	137.7	146.7 (+6.5%)	164.8 (+19.7%)	64.1	64.0	65.9	2.15	2.29	2.50	59.7	60.3	62.2	2.31	2.43	2.65
226.50	168.0	177.3 (+5.5%)	196.2 (+16.8%)	66.1	66.1	68.0	2.54	2.68	2.89	61.2	62.0	63.7	2.74	2.86	3.08
227.00	199.0	208.7 (+4.9%)	228.4 (+14.8%)	67.9	68.3	69.8	2.93	3.05	3.27	62.8	63.9	65.1	3.17	3.27	3.51
227.50	230.6	241.2 (+4.6%)	261.4 (+13.4%)	69.3	71.1	72.1	3.33	3.39	3.63	63.7	66.4	66.7	3.62	3.63	3.91
227.83	252.0	263.5 (+4.6%)	283.8 (+12.6%)	72.7	74.2	75.7	3.47	3.55	3.75	67.0	69.5	70.4	3.76	3.79	4.03

Note: Percentages shown in parentheses under cross-sectional areas represent the percent change in area from the original survey in 2002.

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